RHIC Beam Energy Scan Program: an Update

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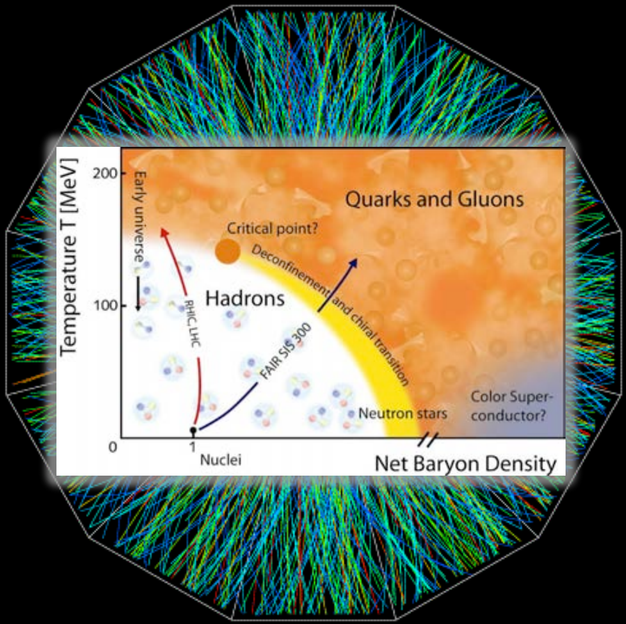
(for the STAR Collaboration)



ZIMÁNYI SCHOOL'17

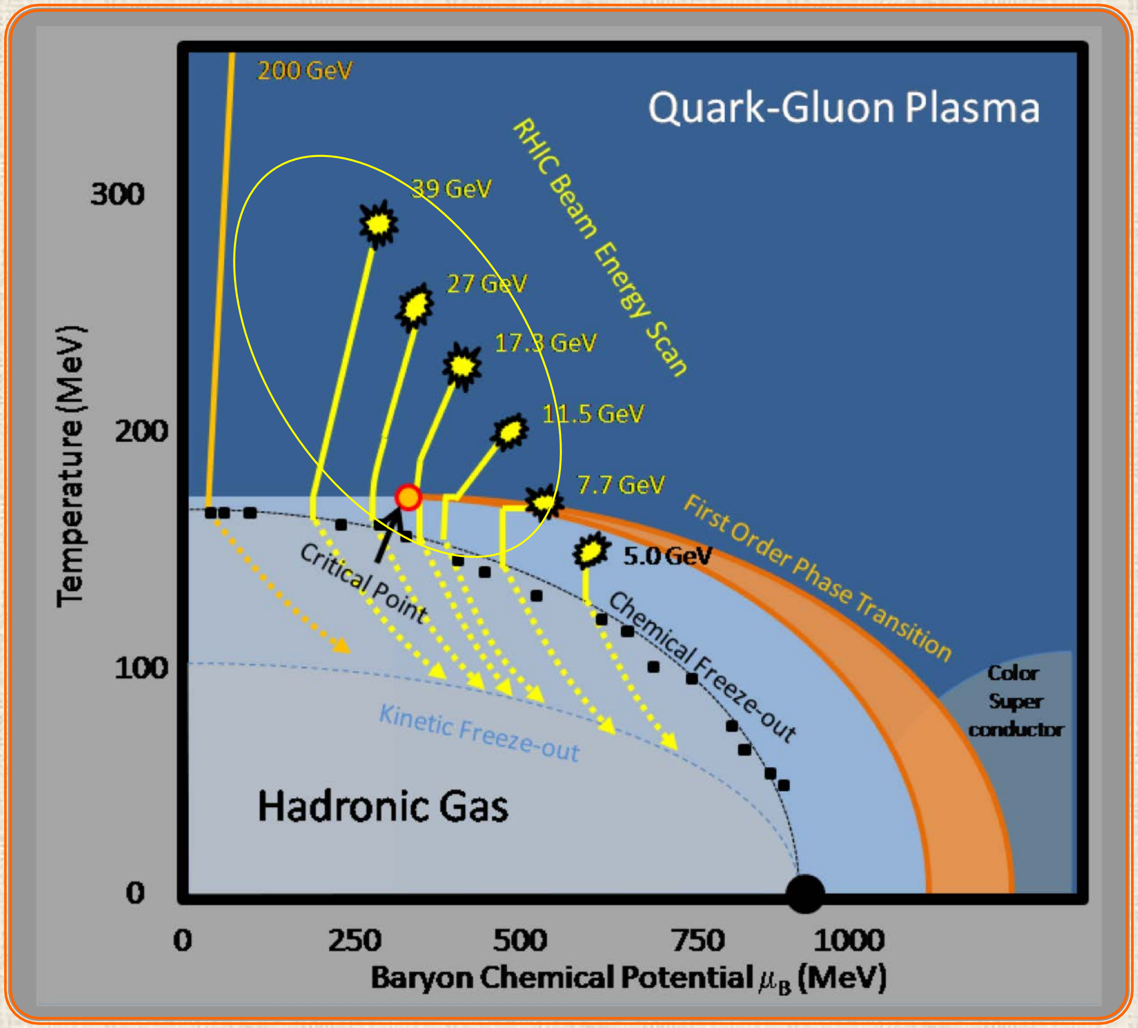
Dec. 4. - Dec. 8., Budapest, Hungary

The RHIC Beam Energy Scan Motivation

1) Turn-off of sQGP signatures

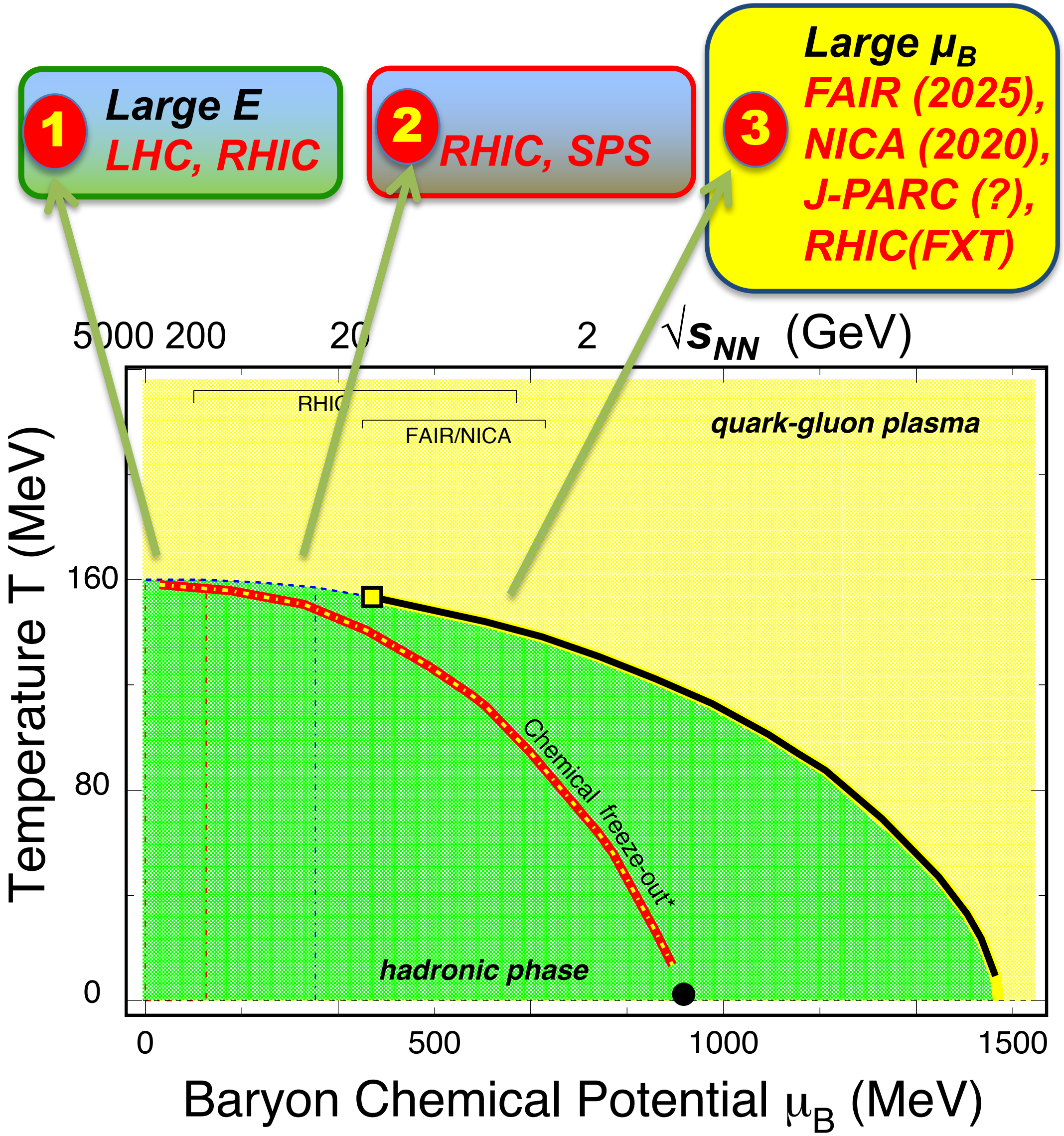
2) Search for the signals of phase boundary

3) Search for the QCD critical point



http://arxiv.org/abs/1007.2613

The QCD Phase Diagram and BES



2000–2012: RHIC+LHC

Top energy program

Discovery of sQGP

- QCD **Critical Point?**
- Chiral effects**?**

2010–2017: RHIC BES-I

7.7, 11.5, 14.5, 19.6, 27, 39, 54.4 GeV

2019–2020: RHIC BES-II

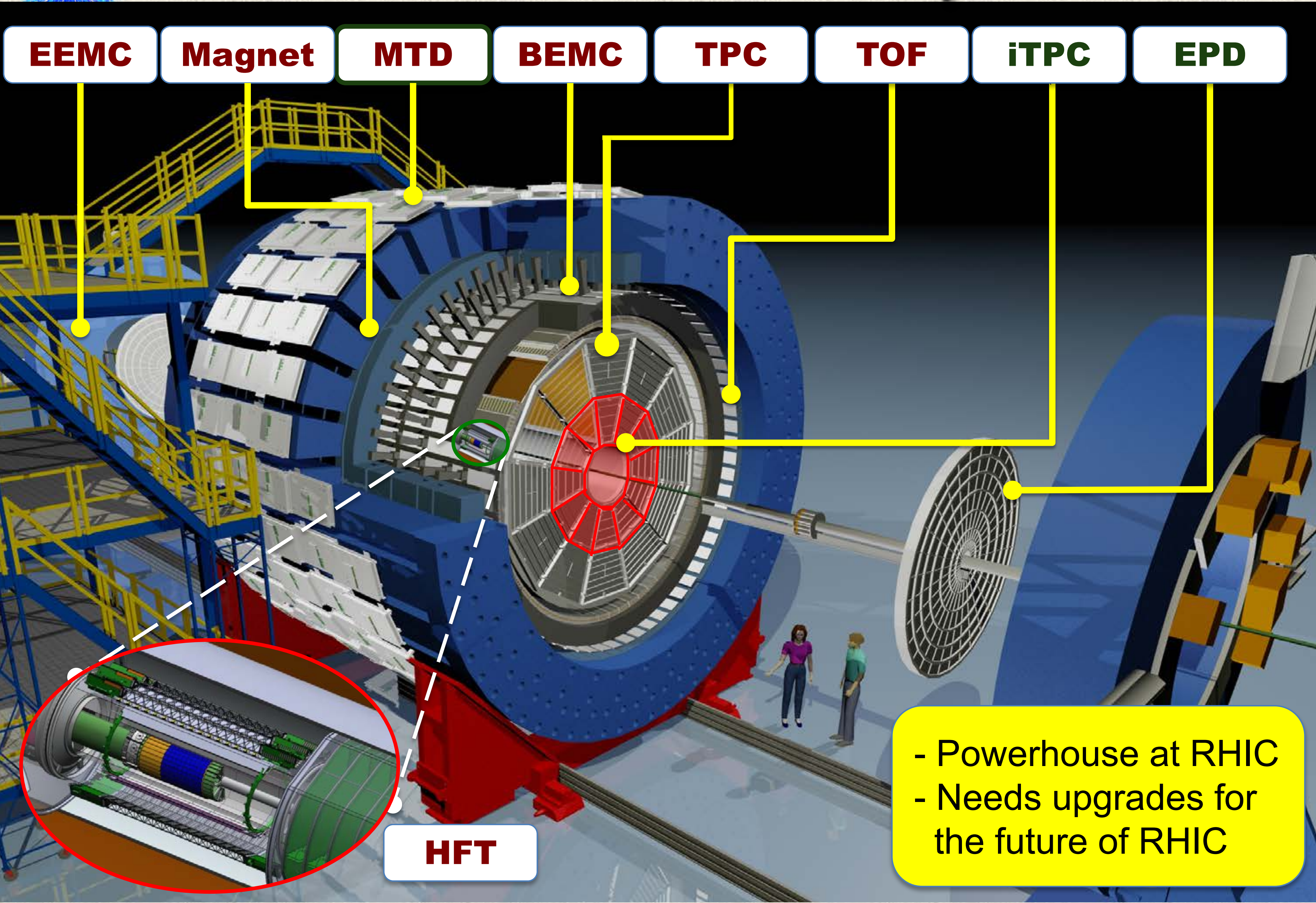
7.7, 9.1, 11.5, 14.5, 19.6 GeV

FXT*: 3.0, 3.5, 3.9, 4.5, 7.7 GeV

2022 – : RHIC+FAIR BES-III

Fixed-target programs

The STAR Detector System



- Powerhouse at RHIC
- Needs upgrades for the future of RHIC

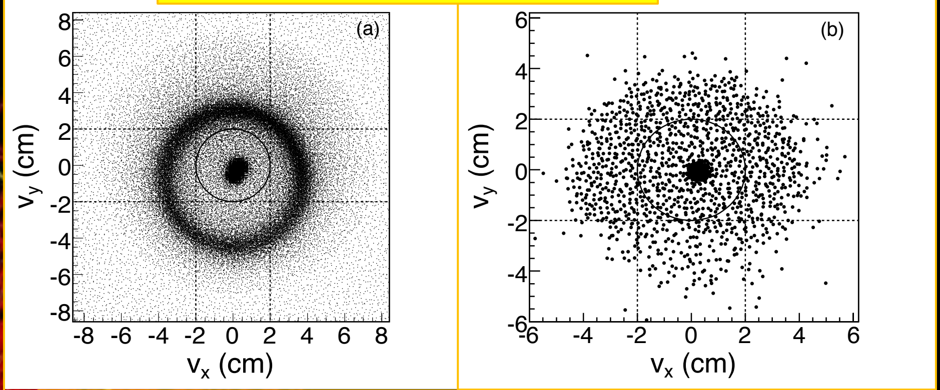
BES-I Au+Au Data Taking

Largest data sets versus collision energy!!!

$\sqrt{s_{NN}}$ [GeV]	events(10^6)	Year
200	350	2010
62.4	67	2010
54.4	300	2017
39	130	2010
27	70	2011
19.6	36	2011
14.5	20	2014
11.5	12	2010
7.7	5	2010
4.9 (FXT)	3.4	2015
4.5 (FXT)	1.3	2015

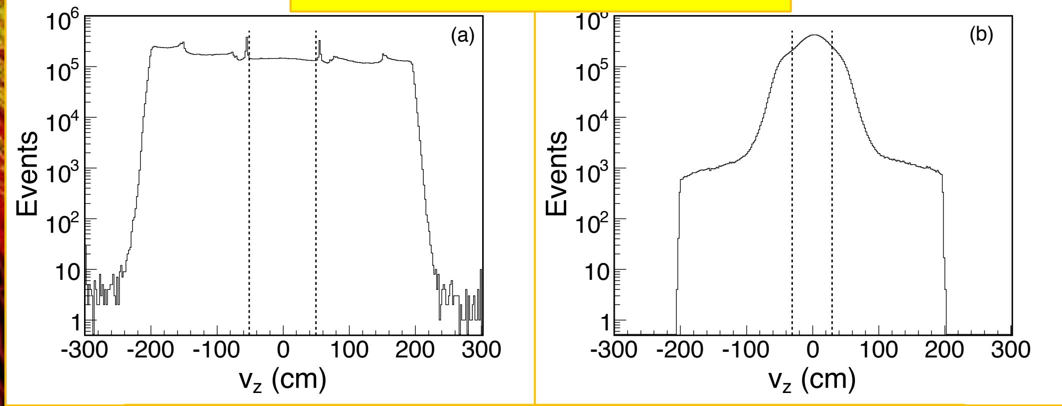
Geometric acceptance @ collider mode remains the same, track density gets lower.
Detector performance generally improves at lower energies.

STAR: Phys.Rev. C **96** (2017) 044904



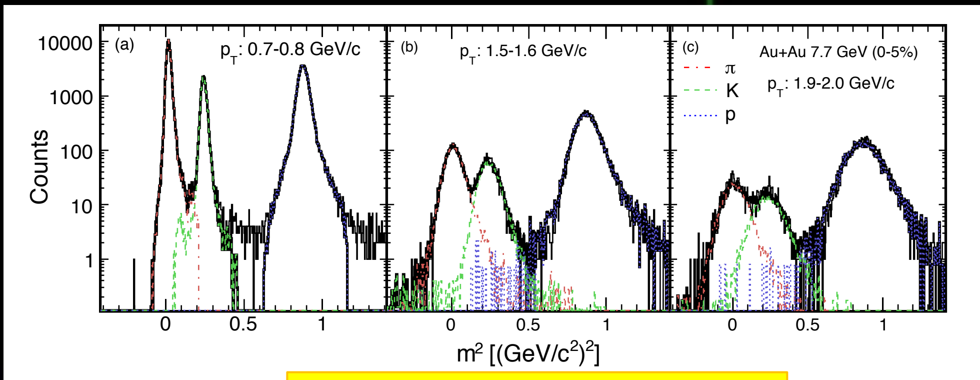
x and y distribution of reconstructed vertex at $\sqrt{s_{NN}}$=7.7 GeV (a) and $\sqrt{s_{NN}}$=39 GeV (b)

STAR: Phys.Rev. C **96** (2017) 044904

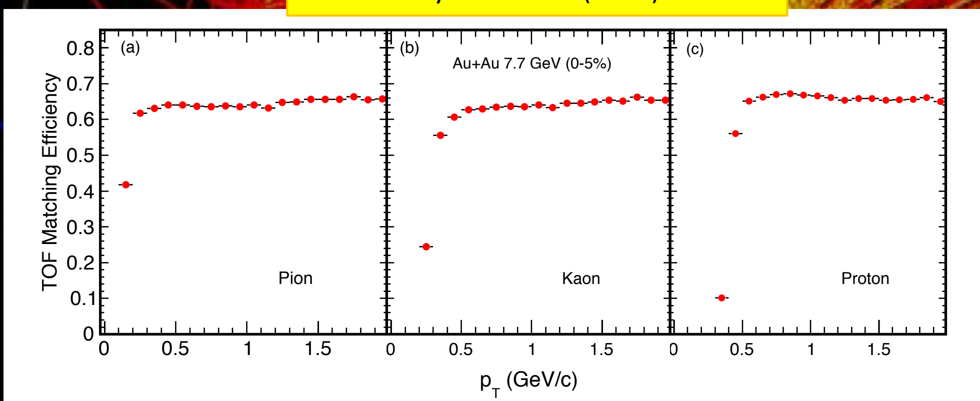


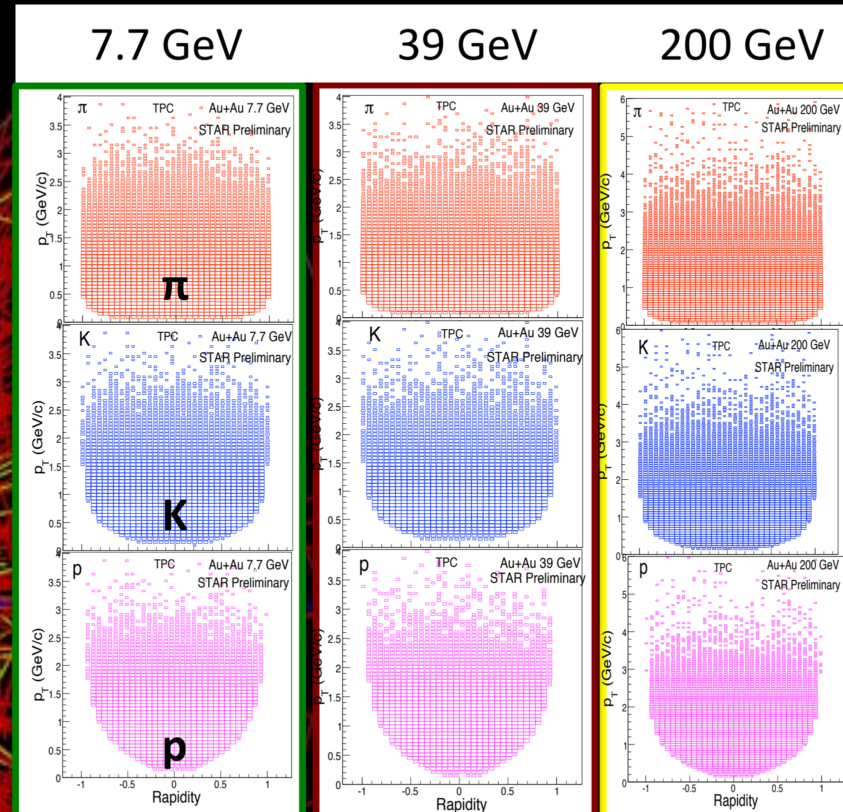
z distribution of reconstructed vertex at $\sqrt{s_{NN}}$=7.7 GeV (a) and $\sqrt{s_{NN}}$=39 GeV (b)

BES-I Au+Au Data Taking



STAR: Phys.Rev. C **96** (2017) 044904

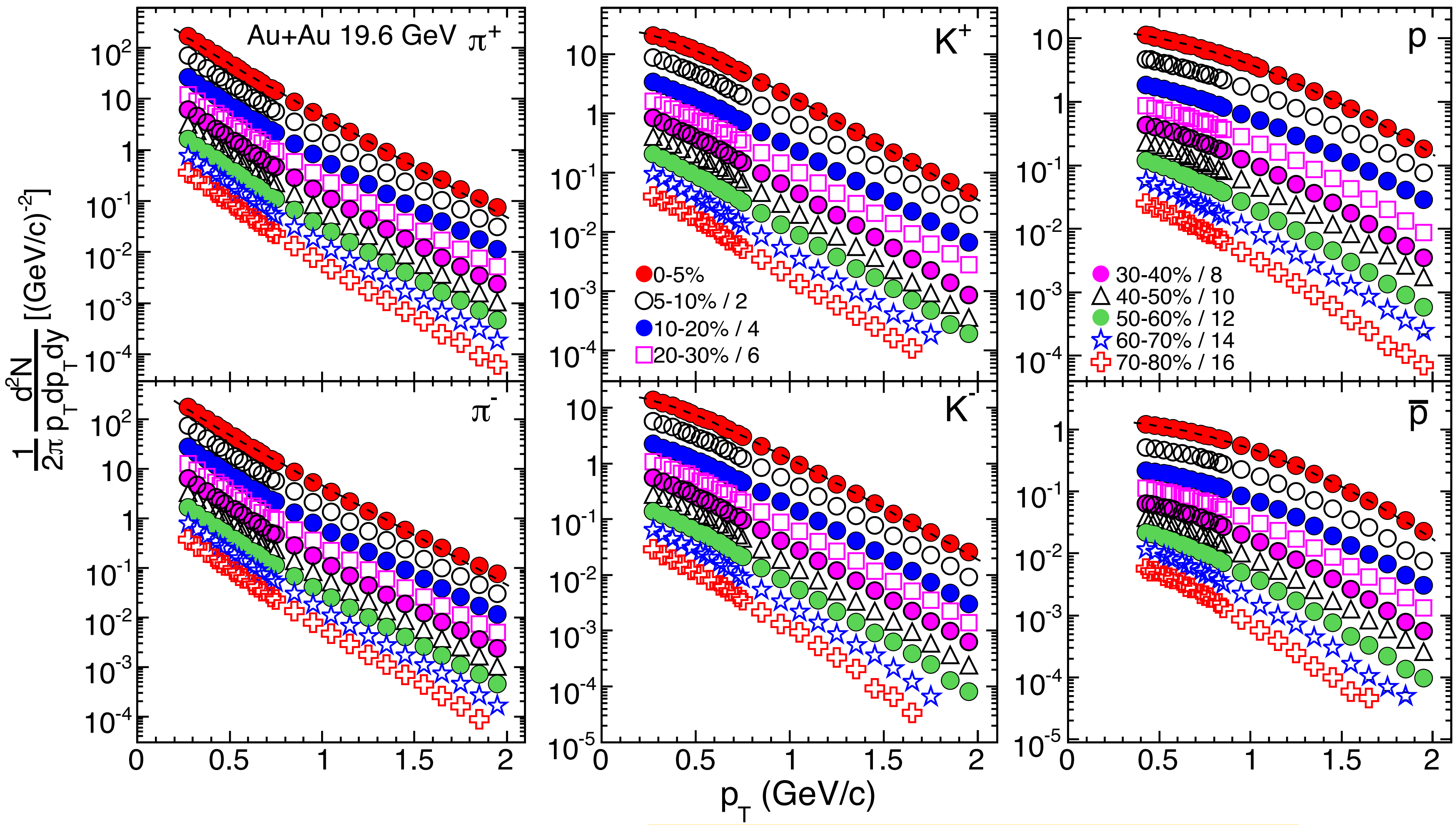




Excellent particle identification capabilities. Large and homogeneous acceptance.
Especially important for fluctuation analysis

Hadron Spectra from BES-I

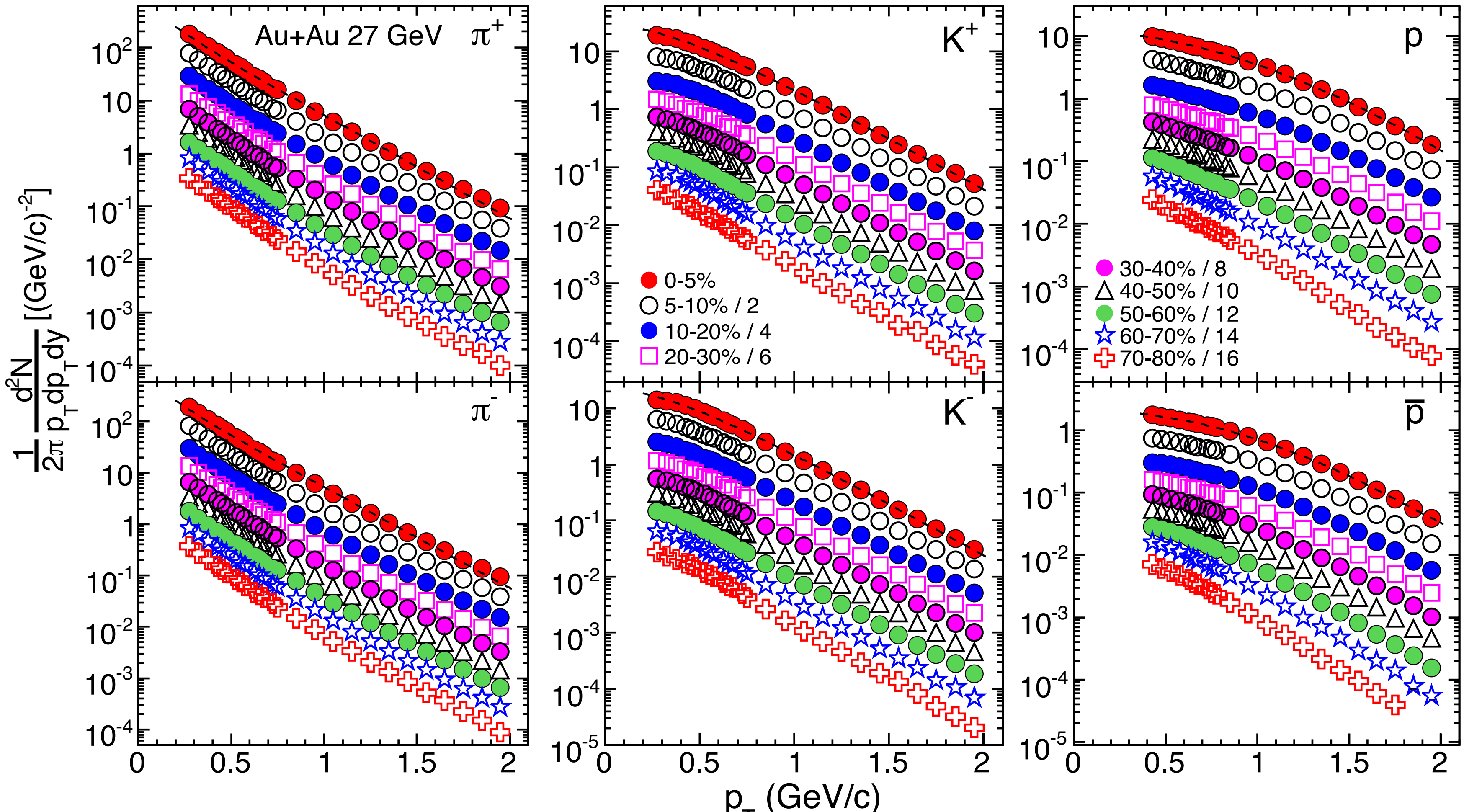
$\sqrt{s_{NN}}$ = *19.6* GeV Au+Au Collisions



STAR: Phys.Rev. C **96** (2017) 044904

Hadron Spectra from BES-I

$\sqrt{s_{NN}}$ = 27 GeV Au+Au Collisions



STAR: Phys.Rev. C **96** (2017) 044904

STAR publications on BES results

1. Inclusive charged hadron elliptic flow in Au + Au collisions at $\sqrt{s_{NN}}$= 7.7-62.4 GeV , Phys. Rev. **C 86** (2012) 54908

2. Observation of an energy-dependent difference in elliptic flow between particles and antiparticles in relativistic heavy ion collisions, Phys. Rev. Lett. **110** (2013) 142301

3. Elliptic flow of identified hadrons in Au+Au collisions at $\sqrt{s_{NN}}$= 7.7-62.4 GeV , Phys. Rev. C **88** (2013) 14902

at the time of my last talk at this conference in 2013

STAR publications on BES results

1. Inclusive charged hadron elliptic flow in Au + Au collisions at $\sqrt{s_{NN}}$= 7.7-62.4 GeV , Phys. Rev. **C 86** (2012) 54908
2. Observation of an energy-dependent difference in elliptic flow between particles and antiparticles in relativistic heavy ion collisions, Phys. Rev. Lett. **110** (2013) 142301
3. Elliptic flow of identified hadrons in Au+Au collisions at $\sqrt{s_{NN}}$= 7.7-62.4 GeV , Phys. Rev. C **88** (2013) 14902
4. Energy Dependence of Moments of Net-proton Multiplicity Distributions at RHIC , Phys.Rev.Lett. **112** (2014) 032302
5. Beam-Energy Dependence of the Directed Flow of Protons, Antiprotons, and Pions in Au+Au Collisions , Phys.Rev.Lett. **112** (2014) 162301
6. Beam energy dependence of moments of the net-charge multiplicity distributions in Au+Au collisions at RHIC , Phys.Rev.Lett. **113** (2014) 092301
7. Beam-energy-dependent two-pion interferometry and the freeze-out eccentricity of pions measured in heavy ion collisions at the STAR detector , Phys.Rev. C **92** (2015) 014904

STAR publications on BES results

8. Energy dependence of acceptance-corrected dielectron excess mass spectrum at mid-rapidity in Au+Au collisions at $\sqrt{s_{NN}}$= 19.6 and 200 GeV, Phys.Lett. B **750** (2017) 64
9. Beam-energy dependence of charge separation along the magnetic field in Au+Au collisions at RHIC , Phys.Rev.Lett. **113** (2014) 052302
10. Energy Dependence of K/π, p/π, and K/p Fluctuations in Au+Au Collisions from $\sqrt{s_{NN}}$ = 7.7 to 200 GeV , Phys.Rev. C **92** (2015) 021901
11. Observation of charge asymmetry dependence of pion elliptic flow and the possible chiral magnetic wave in heavy-ion collisions , Phys.Rev.Lett. **114** (2015) 252302
12. Probing parton dynamics of QCD matter with Ω and φ production, Phys.Rev. C **93** (2016) 021903
13. Beam-energy dependence of charge balance functions from Au + Au collisions at energies available at the BNL Relativistic Heavy Ion Collider , Phys.Rev. C **94** (2016) 024909
14. Centrality dependence of identified particle elliptic flow in relativistic heavy ion collisions at $\sqrt{s_{NN}}$=7.7–62.4 GeV , Phys.Rev. C **93** (2016) 014907
15. Beam Energy Dependence of the Third Harmonic of Azimuthal Correlations in Au+Au Collisions at RHIC , Phys.Rev.Lett. **116** (2016) 112302

STAR publications on BES results

16. Measurement of elliptic flow of light nuclei at $\sqrt{s_{NN}}$= 200, 62.4, 39, 27, 19.6, 11.5, and 7.7 GeV at the BNL Relativistic Heavy Ion Collider, Phys.Rev. C **94** (2016) 034908

17. Energy dependence of J/ψ production in Au+Au collisions at $\sqrt{s_{NN}}$= 39, 62.4 and 200 GeV, Phys.Lett. B **771** (2017) 13

18. Harmonic decomposition of three-particle azimuthal correlations at RHIC, arXiv:1701.06496

19. Global Λ hyperon polarization in nuclear collisions: evidence for the most vortical fluid, **Nature 548**, 62 (2017)

20. Bulk Properties of the Medium Produced in Relativistic Heavy-Ion Collisions from the Beam Energy Scan Program, Phys.Rev. C **96** (2017) 044904

21. Beam Energy Dependence of Jet-Quenching Effects in Au+Au Collisions at $\sqrt{s_{NN}}$ = 7.7, 11.5, 14.5, 19.6, 27, 39, and 62.4 GeV , arXiv:1707.01988

22. Beam-Energy Dependence of Directed Flow of Λ, antiΛ, $K^{\pm}$, K^0_s and φ in Au+Au Collisions , arXiv:1708.07132, accepted to Phys.Rev.Lett.

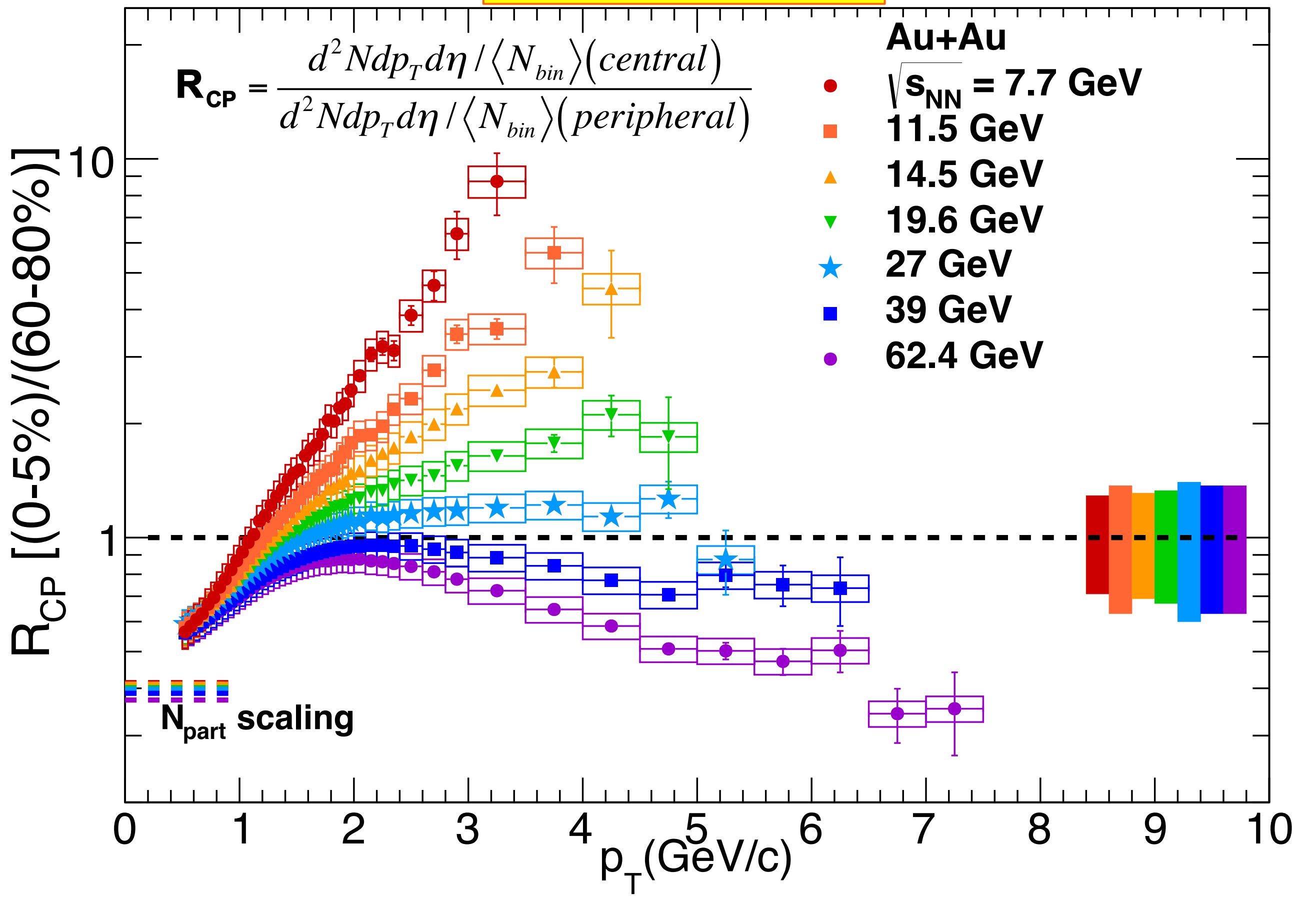
23. Collision Energy Dependence of Moments of Net-Kaon Multiplicity Distributions at RHIC, arXiv:1709.00773

+ many conference proceedings…

1. Turn-off of sQGP signatures

Suppression of Charged Hadrons and its Disappearance

STAR: arXiv:1707.01988



$N_{bin}(b) = N_{coll}(b) = \sigma^{in}_{NN} T_{AB}(b)$

$$T_{AB}(\mathbf{b}) \equiv \int d^2\mathbf{s}\, T_A(\mathbf{s}) T_B(\mathbf{b}-\mathbf{s})$$

$$T_A(\mathbf{b}) \equiv \int dz \rho_A(z, \mathbf{s})$$

$N_{part}(b) =$

$$\int d^2\mathbf{s}\, T_A(\mathbf{s}) \left(1 - e^{-\sigma^{in}_{NN} T_B(\mathbf{s})}\right)$$

$+$

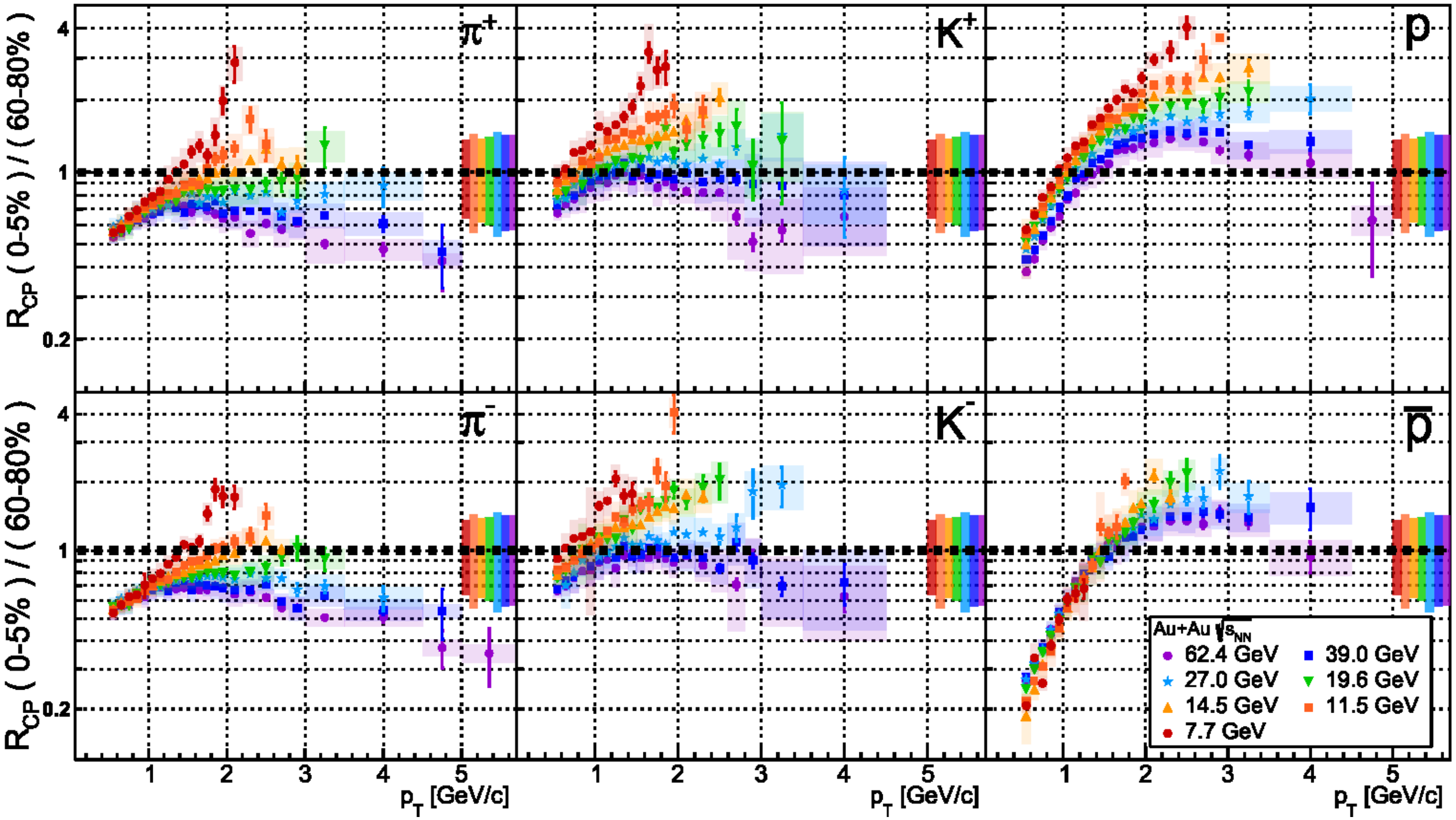
$$\int d^2\mathbf{s}\, T_B(\mathbf{s}-\mathbf{b}) \left(1 - e^{-\sigma^{in}_{NN} T_A(\mathbf{s})}\right)$$

R.P.+M.Š.: arXiv:1611.01533

$R_{CP} \geq 1$ at lower energies - Cronin effect?

Identified particles R_{CP}

STAR: arXiv:1707.01988



(Feed-down subtracted)

High-p_T suppression and its further evolution into enhancement at lower energies is driven by mesons. Baryons remain enhanced up to $\sqrt{s_{NN}}$=62.4 GeV ⇒ Mass driven phenomenon?

Binary collision scaled yield $Y(\langle N_{part} \rangle)$

Take the numerator from R_{CP} and plot it versus centrality:

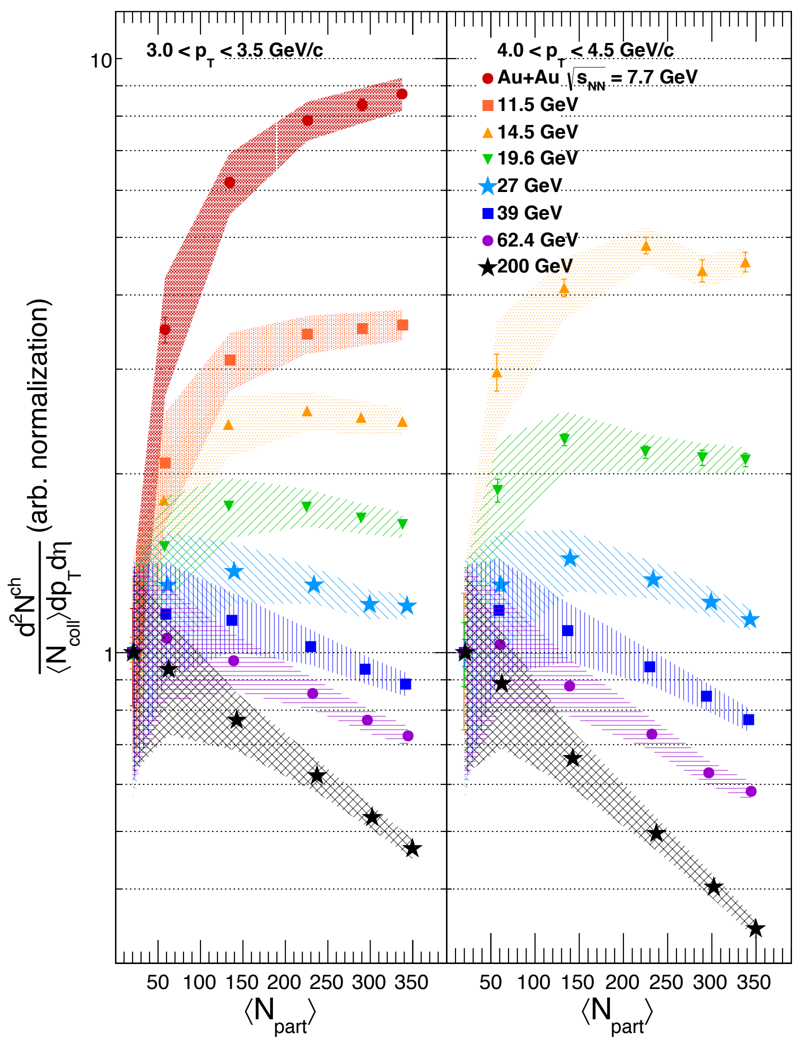
$$Y(\langle N_{\rm part}\rangle) = \frac{1}{\langle N_{\rm coll}\rangle}\frac{d^2N}{dp_{\rm T}d\eta}(\langle N_{\rm part}\rangle)$$

N.B. The peripheral bin contents are in the first bin at low $\langle N_{part} \rangle$ and the central bin's contents are in the last point at high $\langle N_{part} \rangle$.

😊 Examining the full centrality evolution allows determine whether the processes leading to enhancement increase faster or slower than the processes leading toward suppression as a function of $\langle N_{part} \rangle$.

⇒The non-monotonic shape results from the faster increase of jet-quenching compared to the combined phenomena leading to enhancement.*

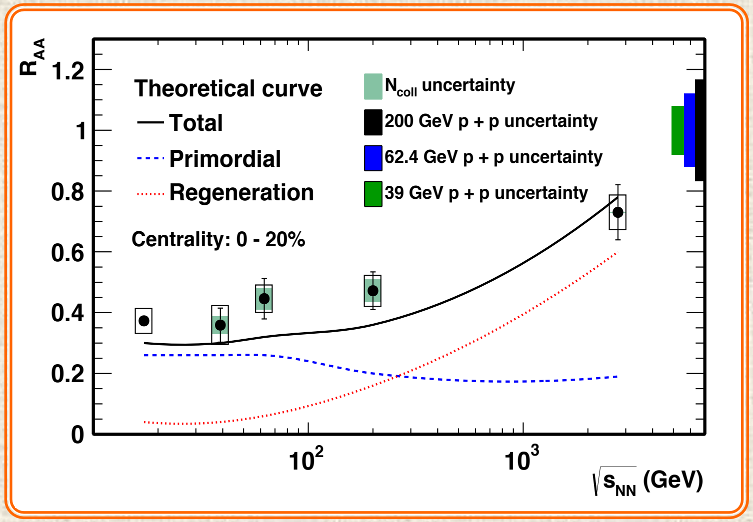
STAR: arXiv:1707.01988



*)Does not rule out the possibility that QGP is also formed @ $\sqrt{s_{NN}} <$ 14.5 GeV

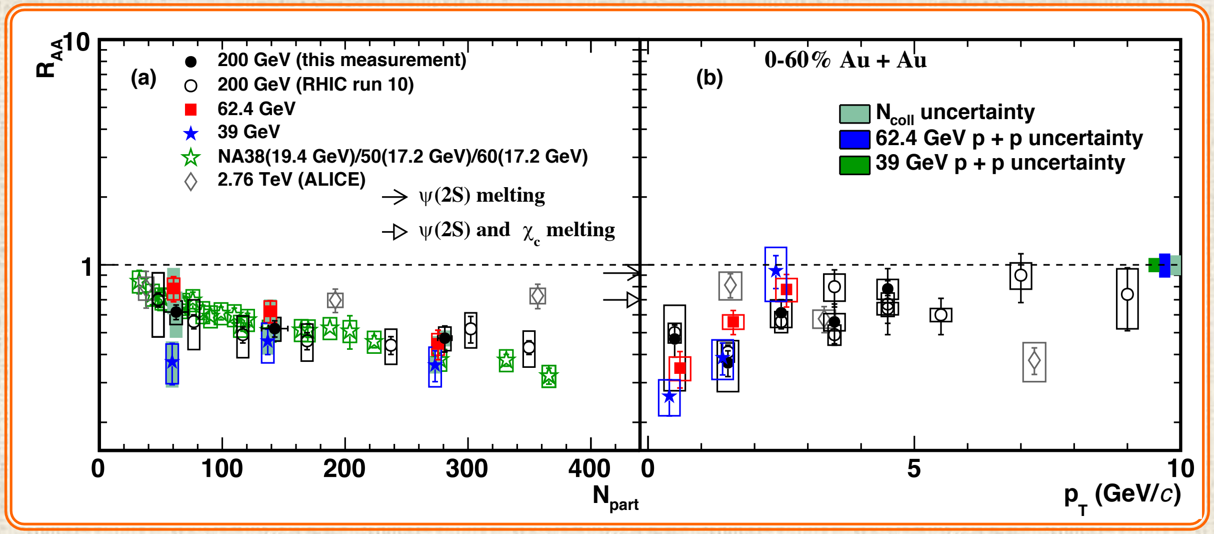
J/ψ Suppression at 39, 62.4 and 200 GeV

STAR: Phys.Lett. B771 (2017) 13-20



$$R_{AA} = \frac{\sigma_{inel}^{pp}}{< N_{coll} >} \frac{d^2N_{AA}/dpTdy}{d^2\sigma_{pp}/dpTdy}$$

- ★ At all three energies R_{AA}<1.
- ★ Consistent* with the suppression of directly produced J/ψ mesons.
- ★ No significant energy dependence of R_{AA} is found within uncertainties.
- ★ Model calculations*, which include direct suppression and regeneration, describe reasonably well the (centrality and) energy dependence of J/ψ production.

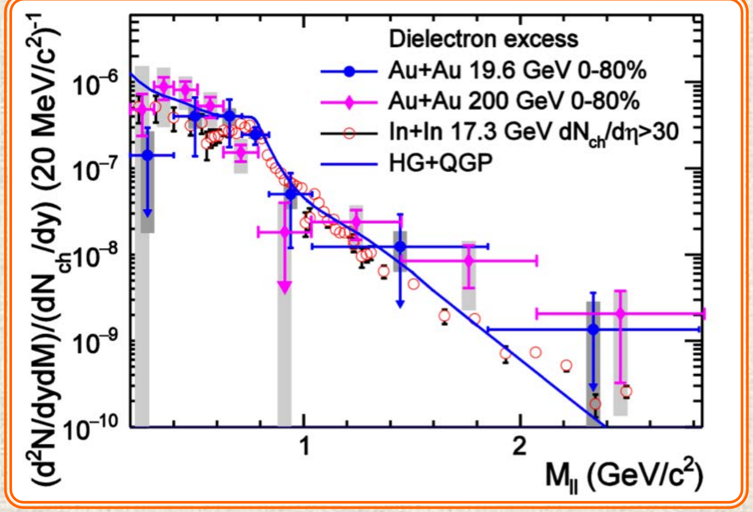


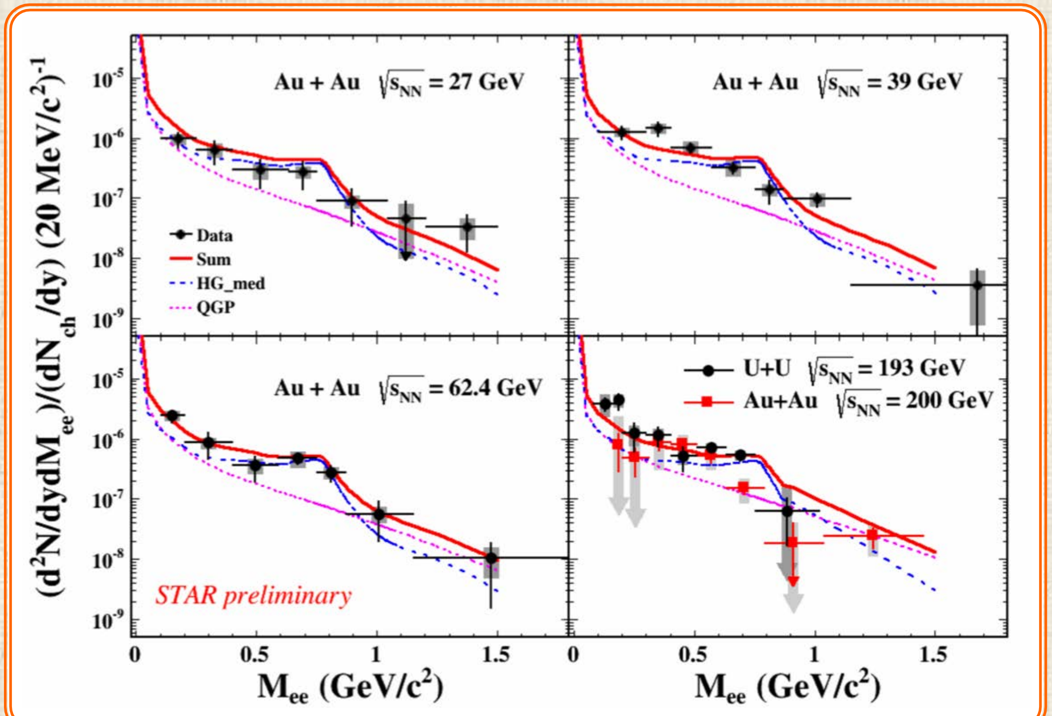
NA38: M.C. Abreu et al., Phys. Lett. B 477, 28 (2000)
ALICE: B. Abelev et al., Phys. Lett. B 734, 314 (2014)

*) Model: X. Zhao and R. Rapp, Phys. Rev. C 82, 064905 (2010)

e^+e^- production at 27,39, 62.4 and 200 GeV

STAR: Phys.Lett. B750 (2015) 64-71



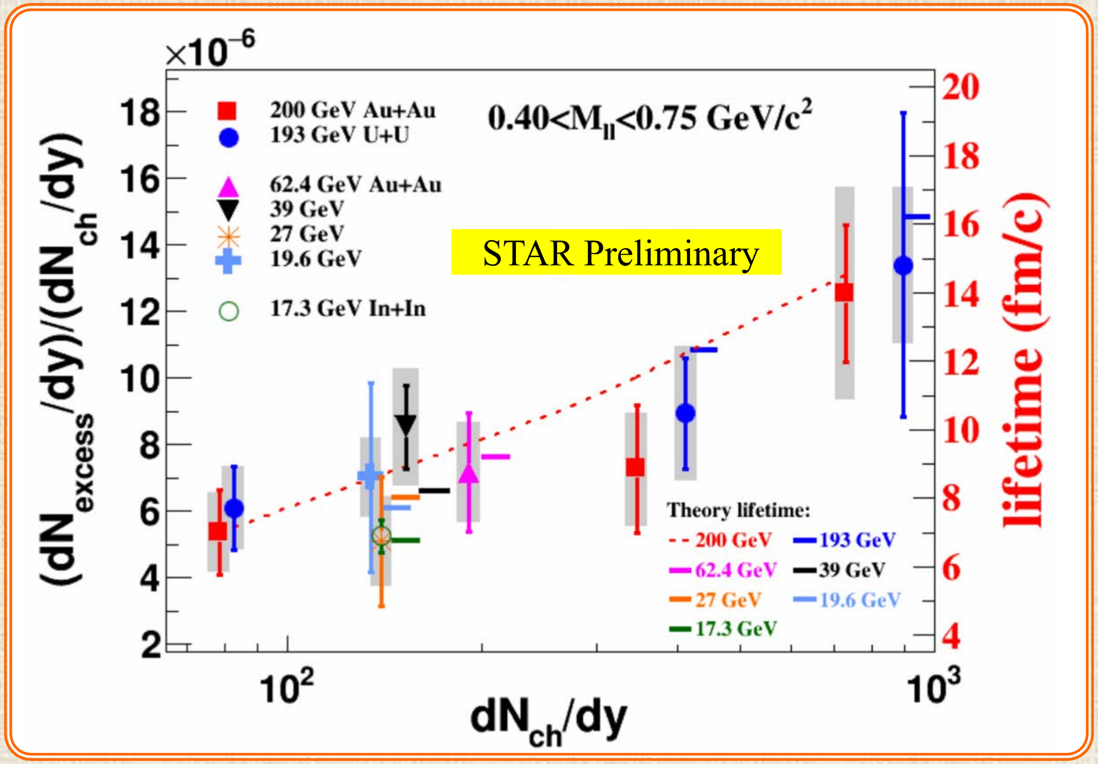


★ Acceptance-corrected excess mass spectra are well described by an effective many body calculations* that incorporate a broadened ρ spectral function in various collision systems and energies.

*) Theory:
R. Rapp, PRC 63 (2001) 054907
and private communication

 The QGP contribution is still significant in the LMR at the lowest energy.
⇒ The integrated yield can be used as a probe for the turn-off of the QGP in the future BES-II program at RHIC.

Connection to fireball lifetime



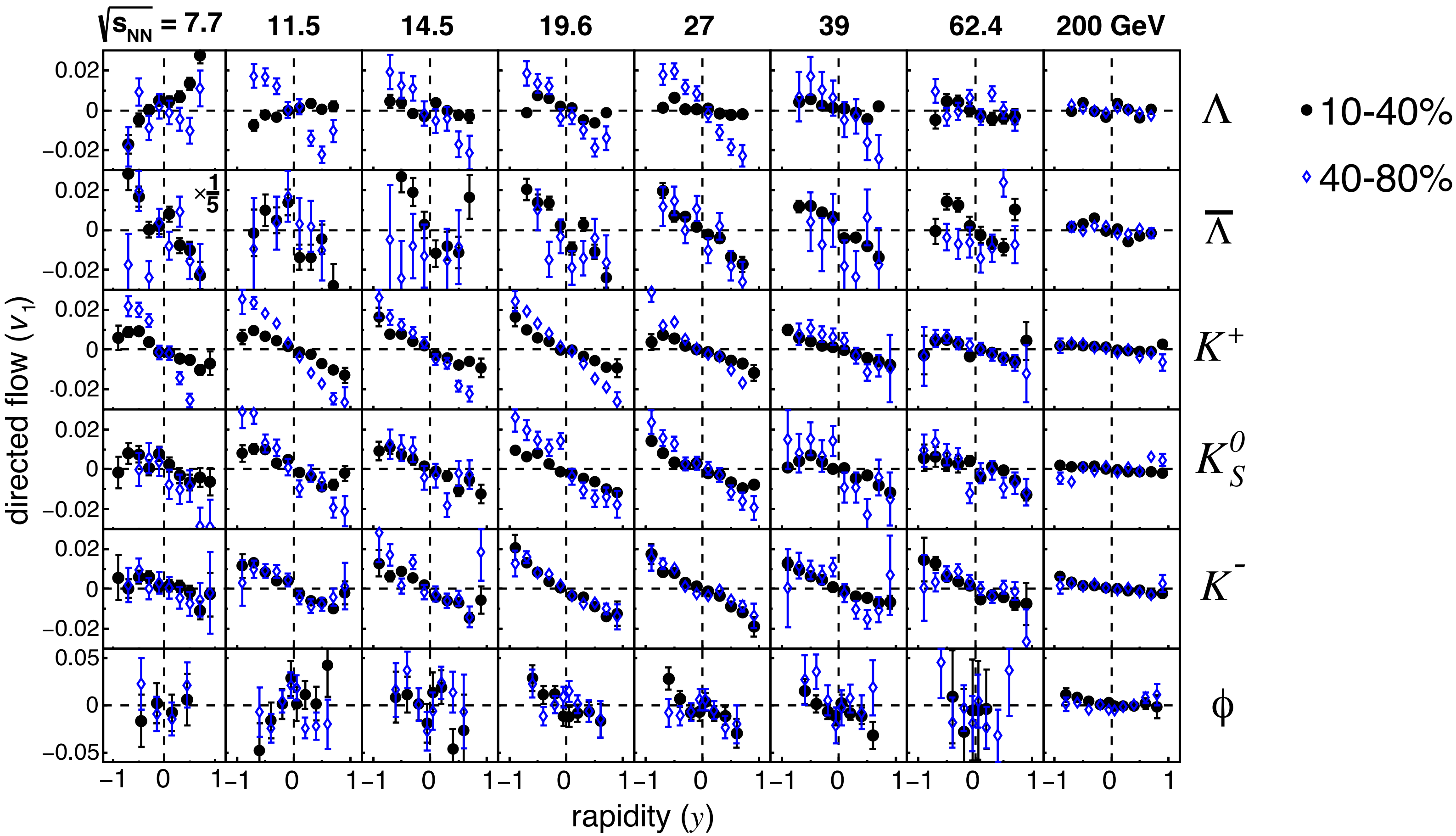
Theory:
R. Rapp, H. van Hees
PLB 753 (2016) 586-590

- ★ From $\sqrt{s_{NN}}$ = 17.3 GeV to $\sqrt{s_{NN}}$ = 200 GeV the integrated excess yield, normalized by dN_{ch}/dy, is proportional to lifetime of the fireball.
- ★ The fireball lifetime increases linearly with the collision centrality (40-80%, 10-40%, 0-10%) is observed too.

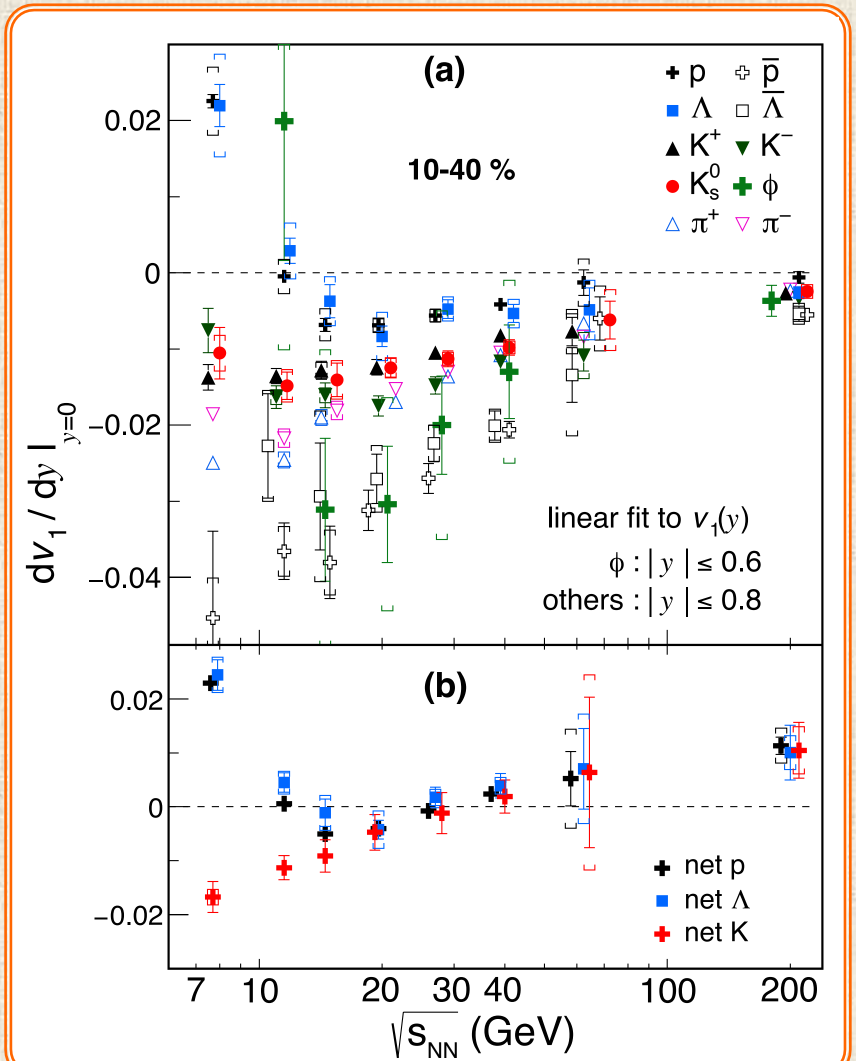
2. Search for the signals of phase boundary: Azimuthal correlations

Directed Flow of Λ, $K^{\pm}$,K^0_s and φ

STAR: arXiv:1708.07132, PRL (accepted)



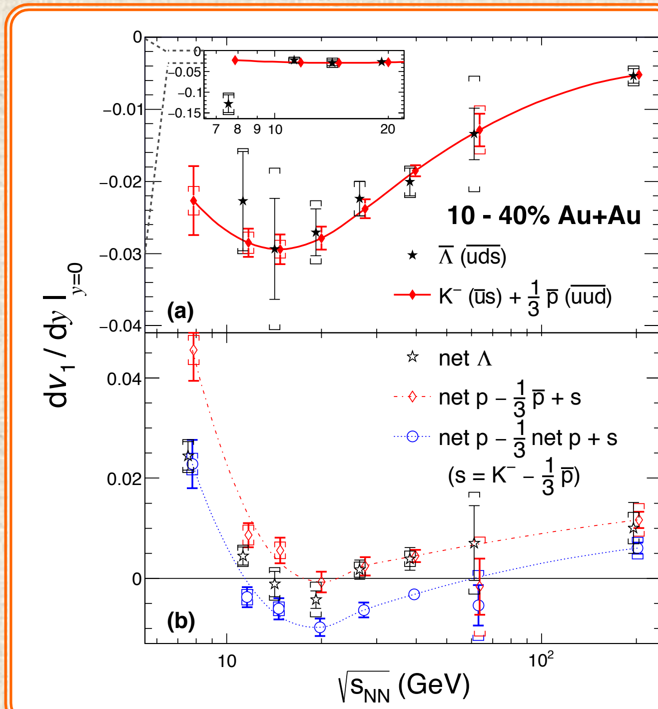
Directed Flow of Λ, $K^{\pm}$, K^0_s, φ and p, π



★ **Proton and Λ v_1 slope:** agree within errors and change sign near 11. 5 GeV

★ **Pion, anti-proton, anti-lambda, $K^{\pm}$ and K_s^0 v_1 slope:** always negative. $K^+ > K^-$.

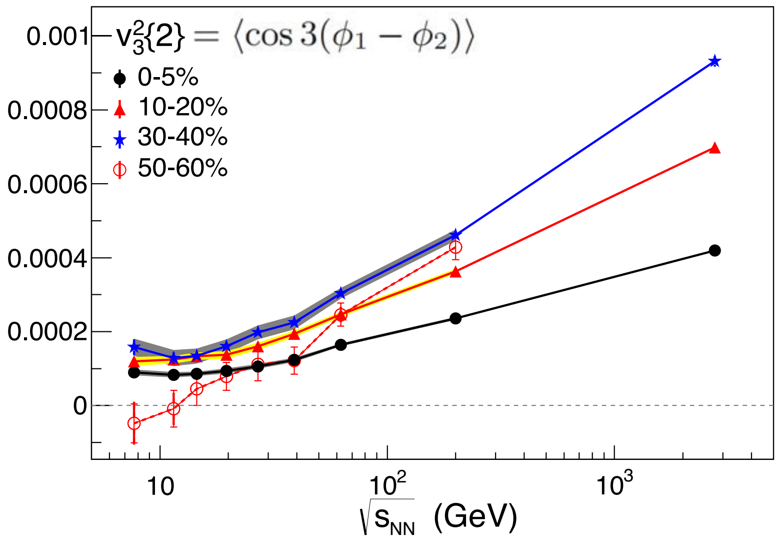
★ **Net-proton and net-Λ v_1 slope:** shows double sign change.

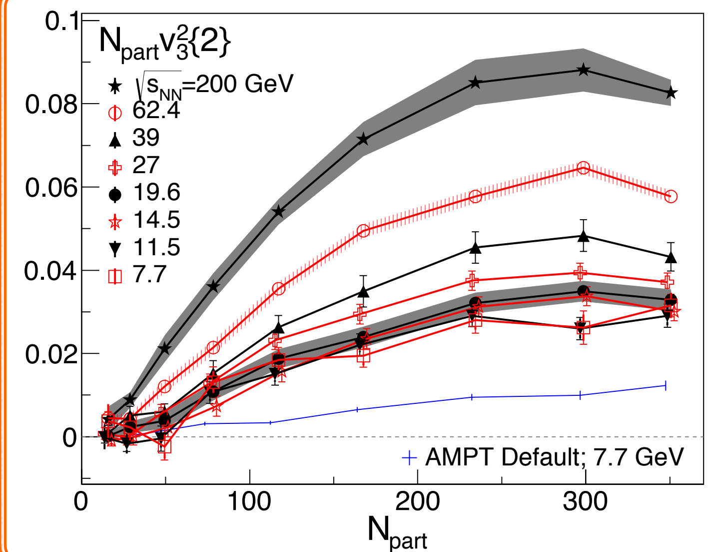


STAR: arXiv:1708.07132, PRL (accepted)

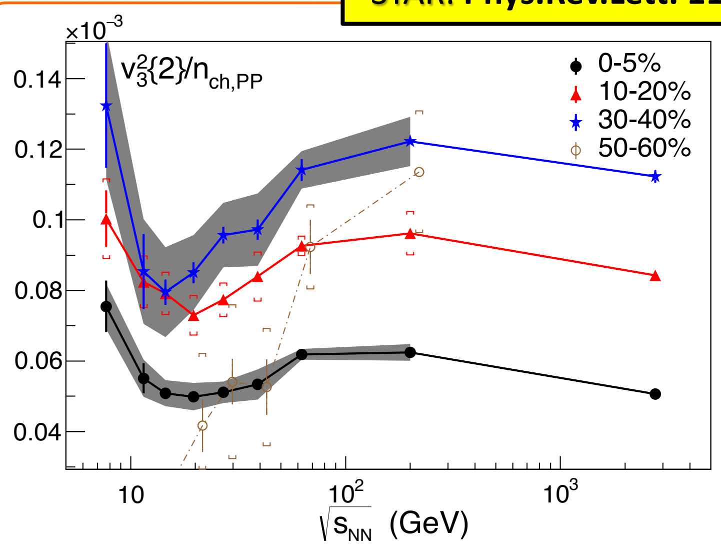
★ Consistent with hadron coalescence of constituent quarks

Energy Dependence of v_3





STAR: Phys.Rev.Lett. 116 (2016) no.11, 112302



- $v_3^2\{2\}$ - directly related to conversion of **initial density anisotropies** in the overlap region into momentum space correlations through subsequent interactions in the expansion (as revealed via large-$\Delta\eta$ narrow-$\Delta\varphi$ **ridge correlations**).
- In hydro $v_3^2\{2\}$ is sensitive to **low viscosity state** of QGP. (Reduction in the pressure expected during a mixed phase should lead to a reduction in the observed correlations.)

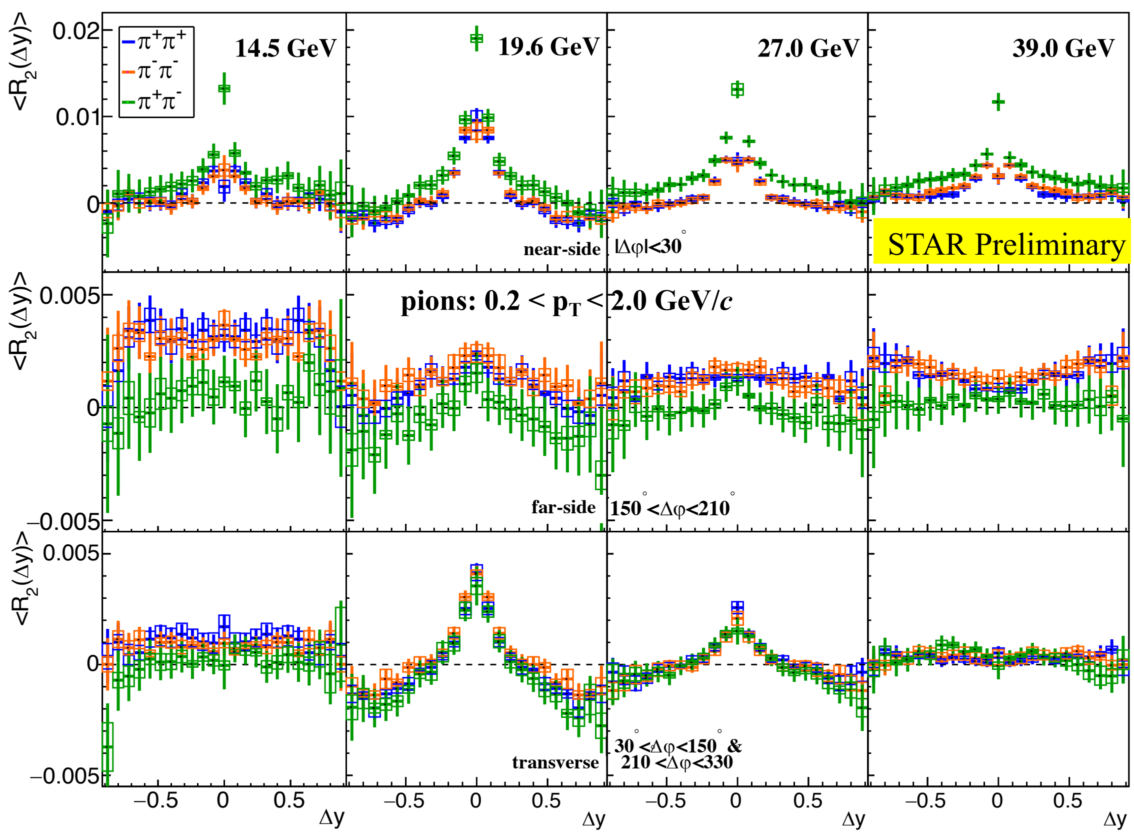
★ **For centralities below 40% down to 7.7 GeV $v_3^2\{2\} \neq 0$.**

☞ **In disagreement with non-QGP models.**

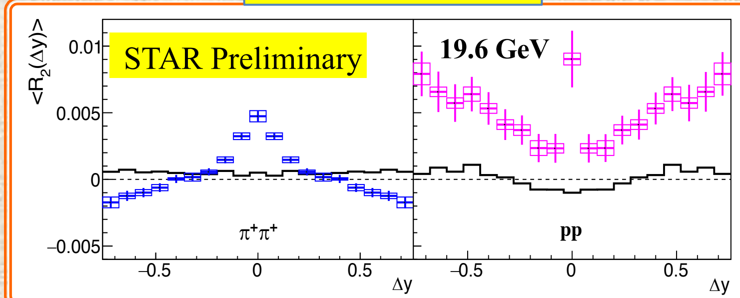
😏 **Maybe QGP is created even at these low energies!?**

★ **$v_3^2\{2\}/n_{ch,PP}$ shows a minimum near $\sqrt{s_{NN}}$=20 GeV.**

Rapidity correlations of $\pi^{\pm}$ in (0-5)% Au-Au



arXiv:1708.03364

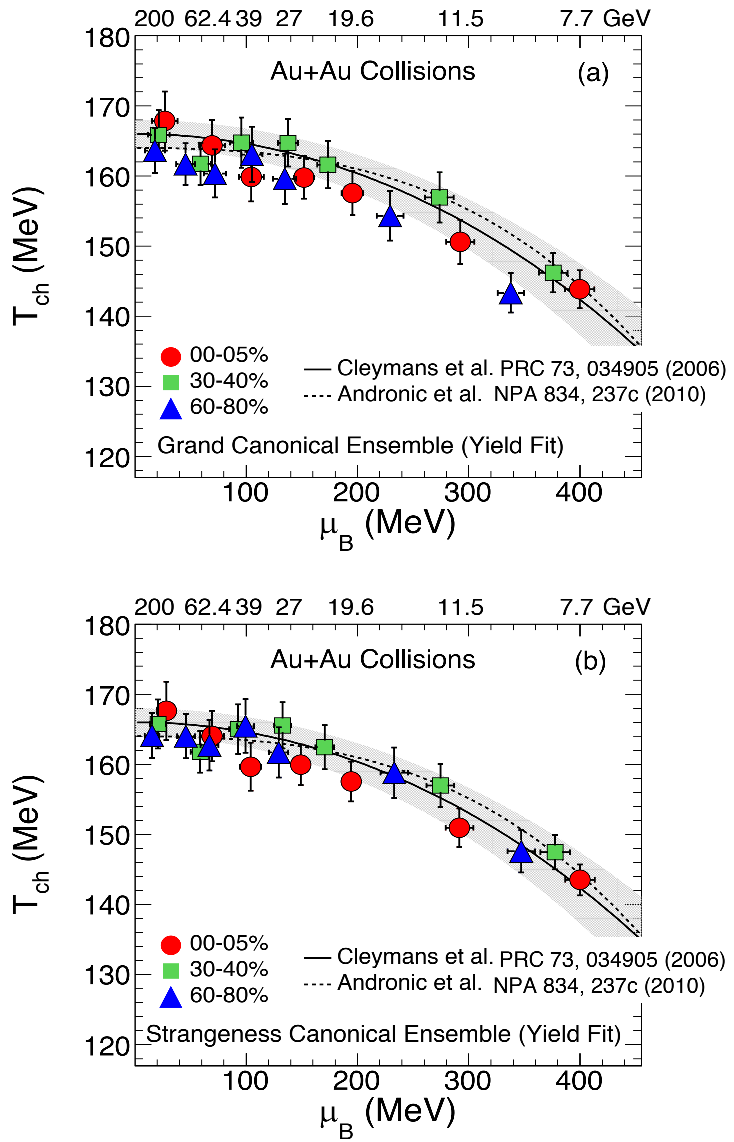


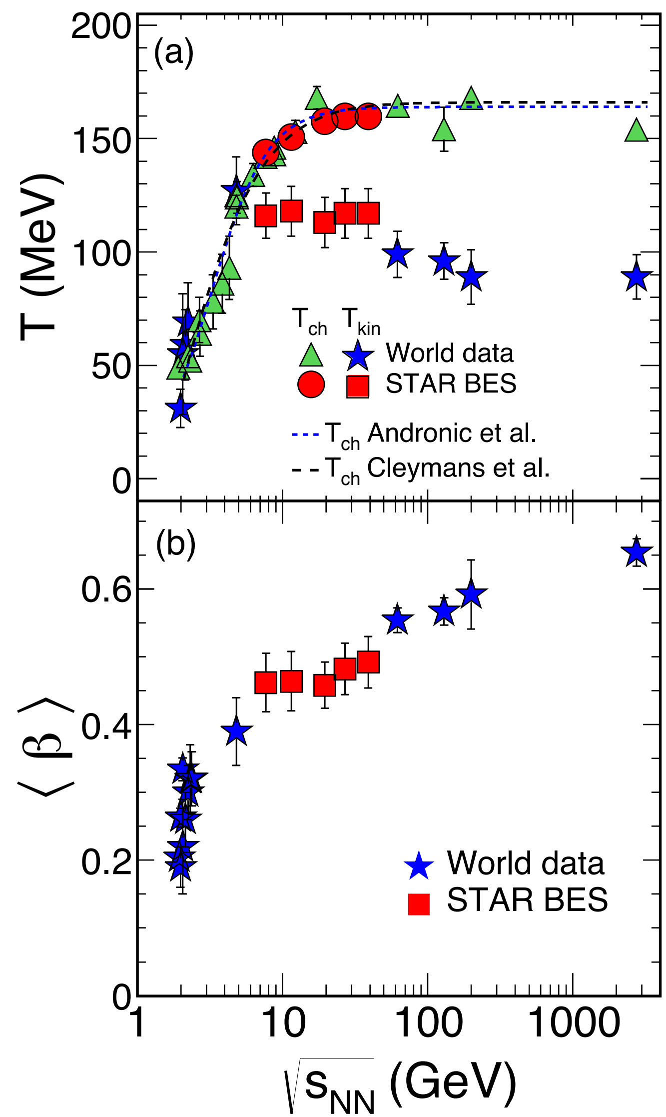
$$R_2(y_1, y_2) = \frac{\langle \rho_2(y_1, y_2) \rangle}{\langle \rho_1(y_1) \rangle \langle \rho_1(y_2) \rangle} - 1$$

- ★ Near-side $|\Delta\phi| < 30^o$ peak around y≈ 0 observed for all energies is stronger in $\pi^+\pi^-$ than in $\pi^{\pm}\pi^{\pm}$. Results from the short-range correlation mechanisms dominant in this $\Delta\phi$ range.
- ★ No significant structure seen in $150^o < \Delta\phi < 210^o$ (far-side) projection.
- ★ Charge-independent and **beam-energy localized** (19.6 and 27 GeV) structure observed in $R_2(\Delta y)$ extending as a ridge in $30^o < \Delta\phi < 150^o$ & $210^o < \Delta\phi < 330^o$!!!
- ★ The UrQMD ($0^o \le \Delta\phi \le 360^o$) does not reproduce the effect neither for $\pi^+\pi^+$ nor for pp correlations.

2. Search for the signals of phase boundary: Bulk properties of matter at freeze-out

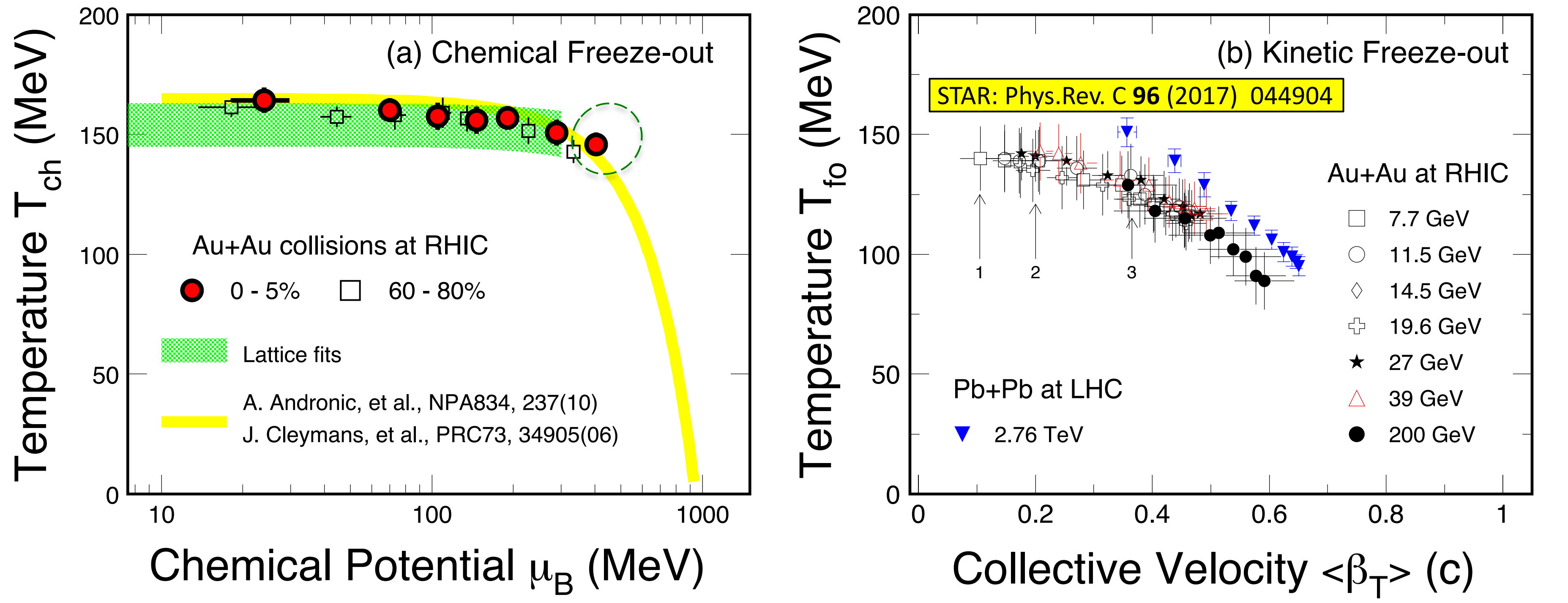
Bulk Properties at Freeze-out





STAR: Phys.Rev. C **96** (2017) 044904

Bulk Properties at Freeze-out



Chemical Freeze-out: (GCE)

- Weak temperature dependence
- Centrality dependence of μ_B!
- LGT calculations* indicate the Critical Region around $\mu_B \approx$ **300 MeV?**

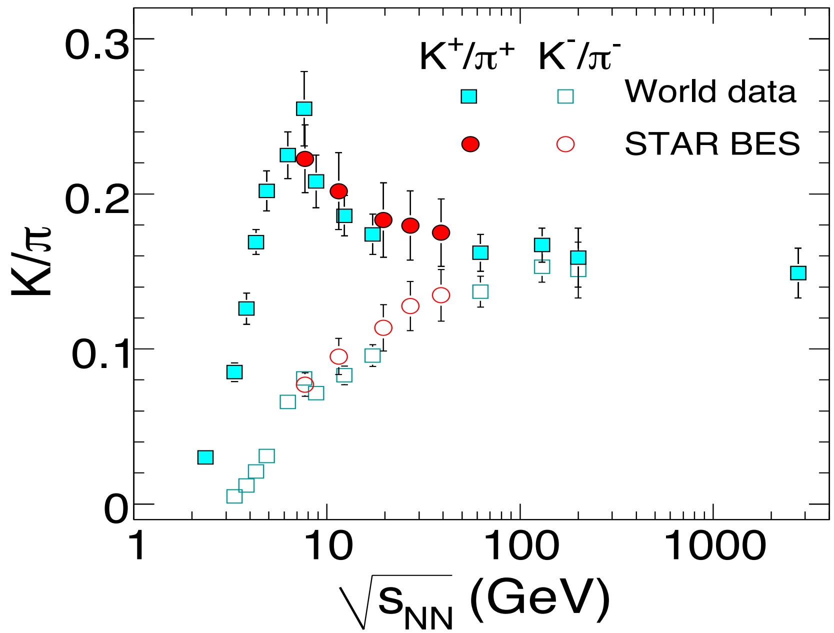
Kinetic Freeze-out:

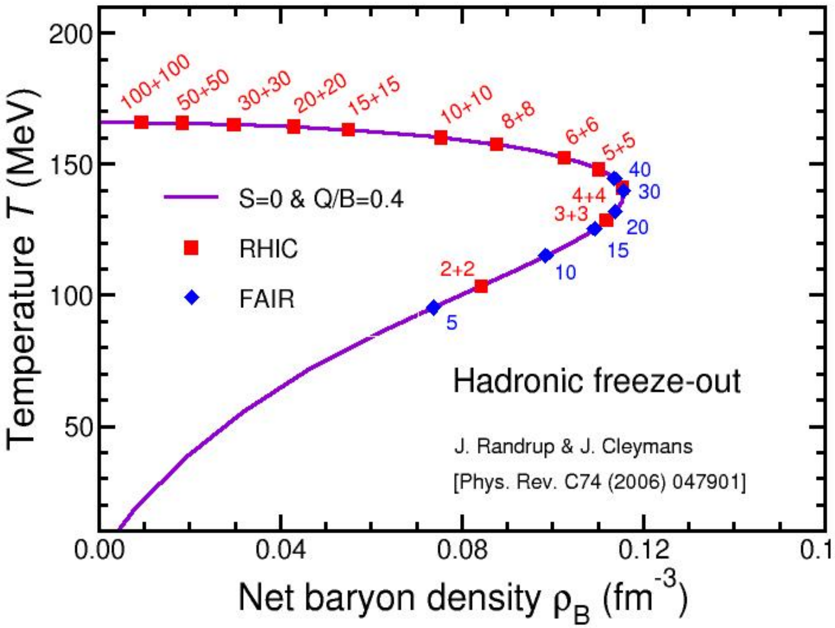
- Central collisions: lower T_{fo} and larger β_T
- **Stronger collectivity at higher energy, even for peripheral collisions**

- ALICE: B.Abelev et al., PRL**109**, 252301 (2012); Phys.Rev. C**88**, 044910 (2013).
- STAR: J. Adams, et al., NPA**757**, 102 (2005); **STAR**: Phys.Rev. C**96** 044904 (2017)

*) S. Mukherjee: Private communications. August, 2012

K/π Ratios and Baryon Density

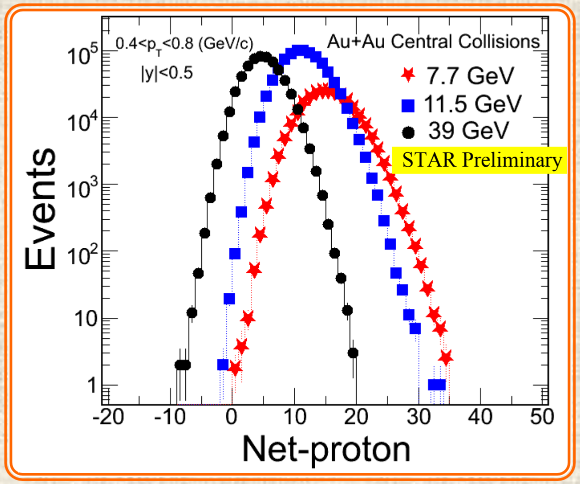




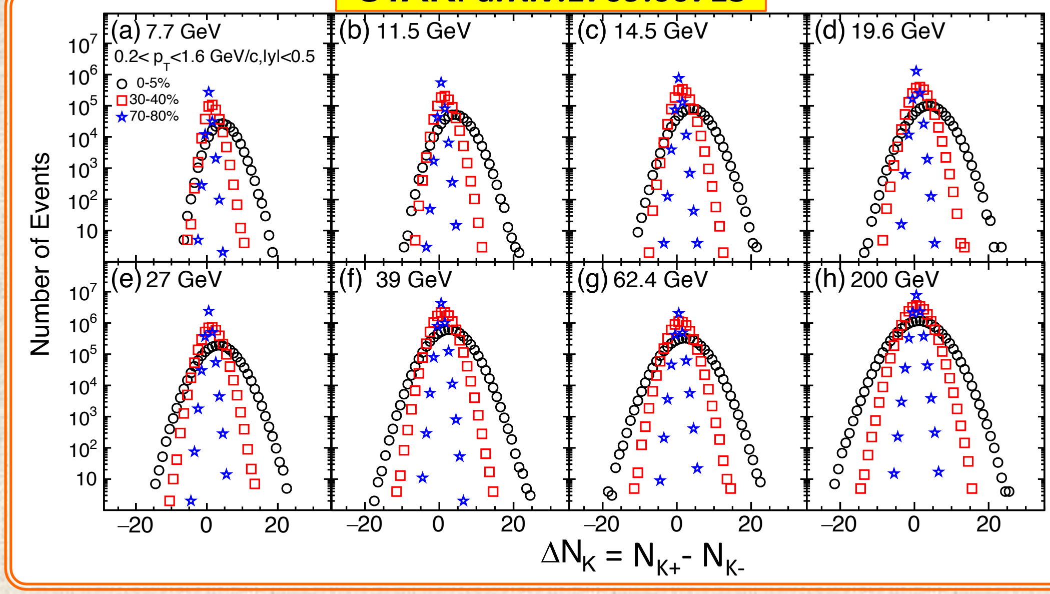
1) The K^+/π ratio peaks at $\sqrt{s_{NN}}$ ~ 8 GeV,
   K^-/π ratio merges with K^+/π at higher collision energy
2) Model: **Net baryon density peaks at $\sqrt{s_{NN}}$ ~ 8 GeV**
3) At **$\sqrt{s_{NN}}$ > 8 GeV, pair production becomes important**

3. Search for the QCD CEP: Fluctuations of conserved quantities

Net-K and net-p distributions



STAR: arXiv:1709.00713



N = net-proton or ΔN_K

From P(N) to cumulants

$\delta N = N - \langle N \rangle$

$C_1 = \langle N \rangle$

$C_2 = \langle (\delta N)^2 \rangle$

$C_3 = \langle (\delta N)^3 \rangle$

$C_4 = \langle (\delta N)^4 \rangle - 3\langle (\delta N)^2 \rangle^2$

Mean (M), variance (σ), skewness S and kurtoisis (κ)

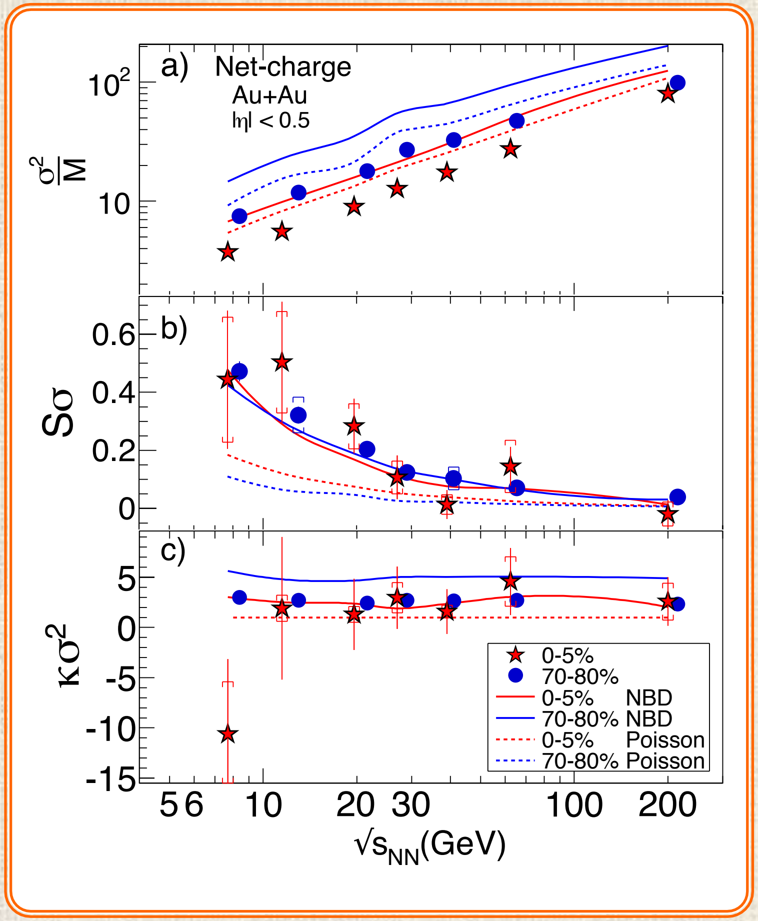
$M = C_1$, $\sigma^2 = C_2$, $S = C_3/(C_2)^{3/2}$, $\kappa = C_4/(C_2)^2$

From cumulants to multi-particle correlators

$$\hat{\kappa}_1 = C_1$$
$$\hat{\kappa}_2 = C_2 - C_1$$
$$\hat{\kappa}_3 = C_3 - 3C_2 + 2C_1$$
$$\hat{\kappa}_4 = C_4 - 6C_3 + 11C_2 - 6C_1$$

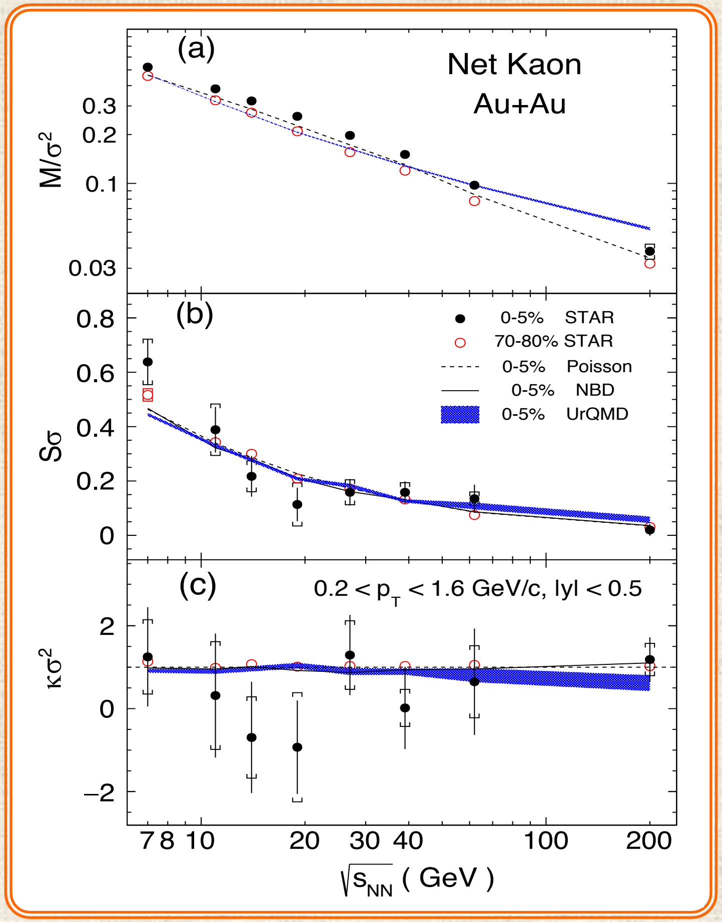
Higher Moments of Net-Q, -K, -p

STAR: PRL. 113 (2014) 092301



$$\sigma^2/M = C_2/C_1$$
$$M/\sigma^2 = C_1/C_2$$
$$S\sigma = C_3/C_2$$
$$\kappa\sigma^2 = C_4/C_2$$

STAR: arXiv:1709.00713



☹ The net-Q shows flat energy dependence.
☹ The net-Kaon shows flat energy dependence.

M. Šumbera

Higher Moments of Net-Q, -K, -p

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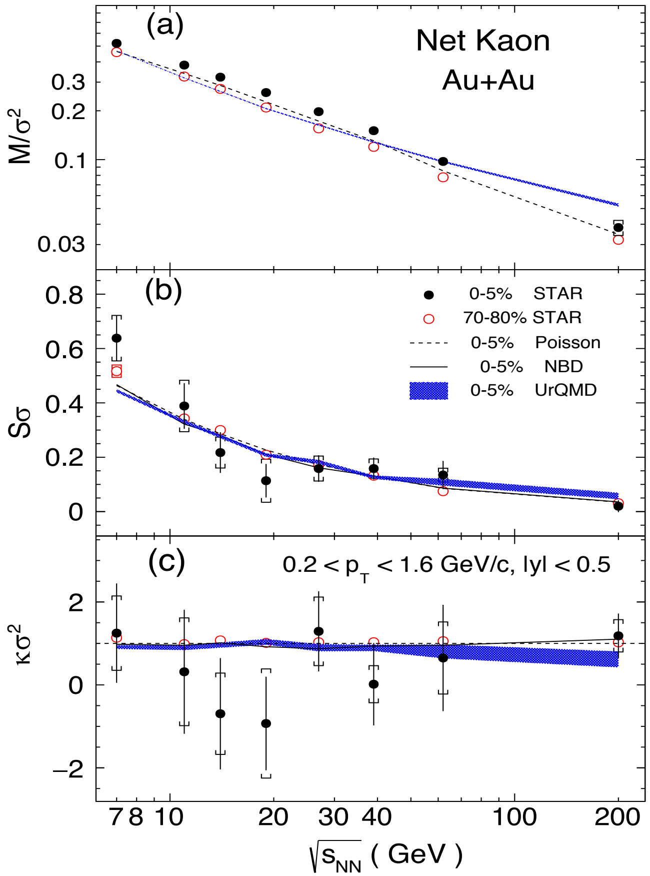
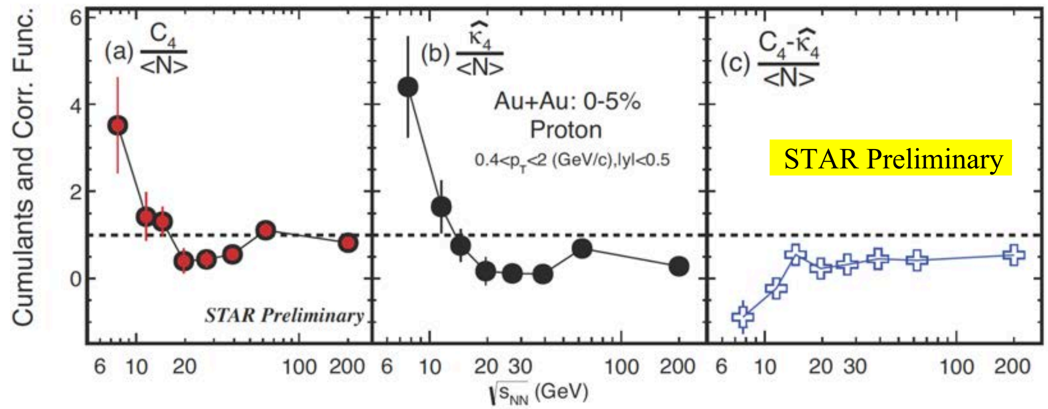




$M/\sigma^2 = C_1/C_2$
$S\sigma = C_3/C_2$
$\kappa\sigma^2 = C_4/C_2$

☹ The net-Kaon shows flat energy dependence.

★ Net-p shows **non-monotonic energy dependence** in the most central Au+Au collisions starting at **$\sqrt{s_{NN}}$** < 27 GeV!

Beam Energy Scan Phase- II

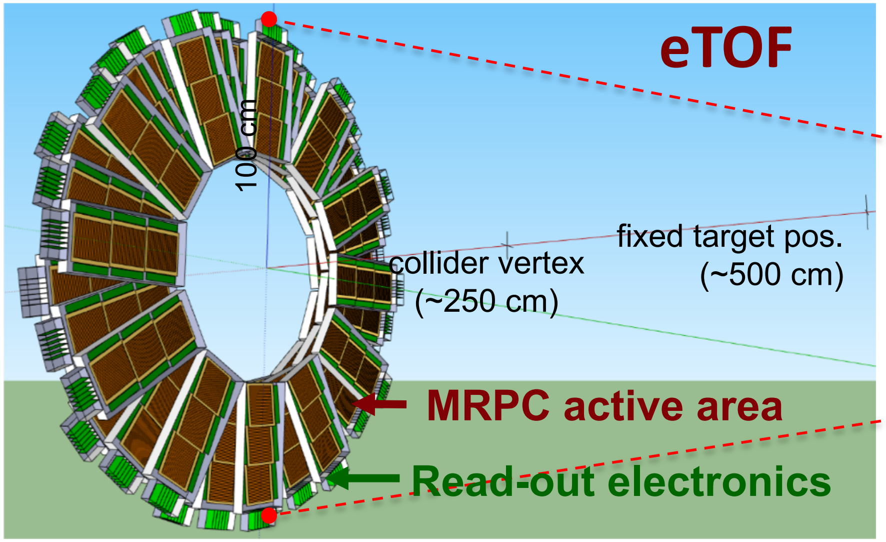
2019-2020: BES-II at RHIC

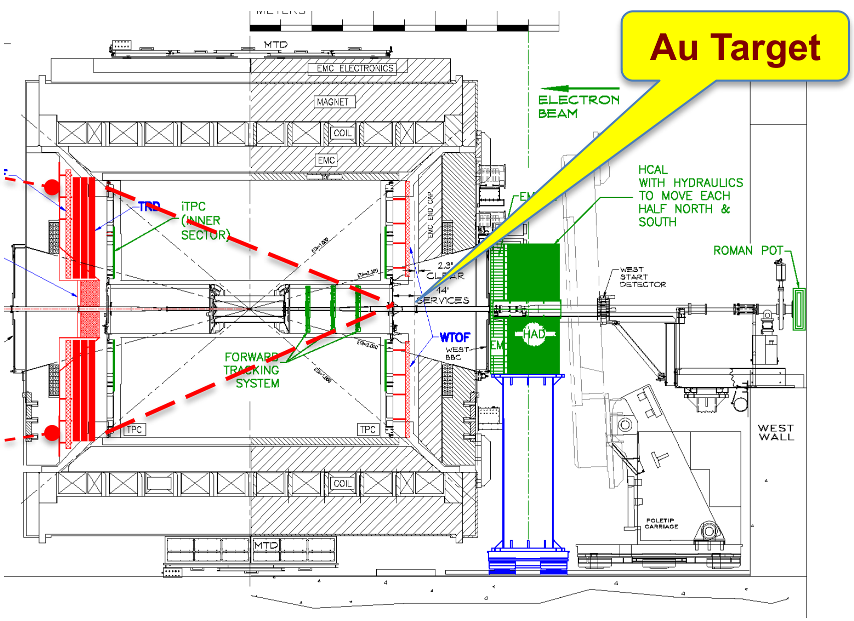
$\sqrt{s_{NN}}$ (GeV)	Events (10^6)	BES-II / BES-I	Weeks	μ_B (MeV)	T_{CH} (MeV)
200	350	2010		25	166
62.4	67	2010		73	165
54.4	**1200**	**2017**			
39	39	2010		112	164
27	70	2011		156	162
19.6	**400** / 36	**2019-20** / 2011	**3**	206	160
14.5	**300** / 20	**2019-20** / 2014	**2.5**	264	156
11.5	**230** / 12	**2019-20** / 2010	**5**	315	152
9.1	**160** / 0.3	**2019-20** / 2008	**9.5**	355	140
7.7	**100** / 4	**2019-20** / 2010	**14**	420	140

Precision measurements, map the QCD phase diagram

$200 < \mu_B < 420$MeV

CBM Phase-0 Exp: eTOF@STAR





Install, commission and use 10% of the CBM TOF modules, including the read-out chains at STAR, starting in 2019

CBM participating in RHIC Beam Energy BES-II in 2019-2020:

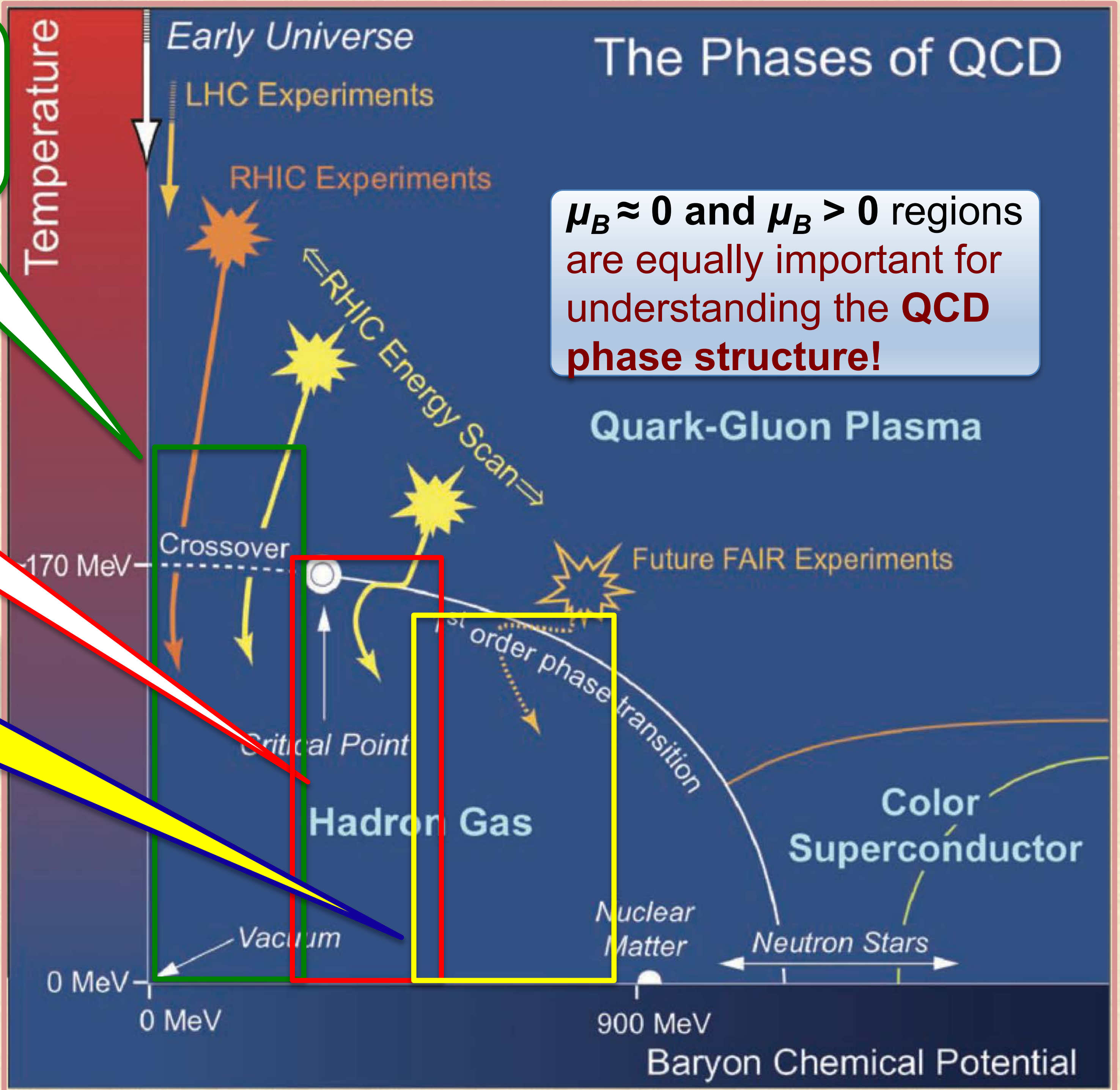
- Complementary to part of CBM's physics program:
  $\sqrt{s_{NN}}$ = **3**, **3.5**, **3.9**, **4,5**, 7.7 GeV (**$750 \leq \mu_B \leq 420$ MeV**)
  especially for ***B-*** & ***s-hadrons*** production and fluctuations

Adapted from Nu Xu

LHC+RHIC
QGP properties
$\mu_B \approx 0$
now - **2026**

RHIC BES-II
collider mode
$200 < \mu_B < 420$ MeV
2019 & 2020

Fixed-target BES-III
$350 < \mu_B < 750$ MeV
2019 – **CBM**



$\mu_B \approx 0$ and $\mu_B > 0$ regions are equally important for understanding the **QCD phase structure!**

Adapted from Nu Xu

M. Šumbera

Summary

- **STAR results from BES program covering large μ_B range provide important constraint on the QCD phase diagram:**
  - High-p_T suppression and its further evolution into enhancement at lower $\sqrt{s_{NN}}$ is driven by mesons. Baryons up to $\sqrt{s_{NN}}$=62.4 GeV remain enhanced.
  - No significant energy dependence of the J/ψ suppression from SPS to RHIC was found.
  - Integrated excess yield of LMR di-electrons normalized by dN_{ch}/dy, is proportional to lifetime of fireball from $\sqrt{s_{NN}}$ = 17.3 GeV to $\sqrt{s_{NN}}$ = 200 GeV.
  - Directed flow slopes of net-proton and net-Λ $dv_1/dy|_{y=0}$ show double sign change.
  - For centralities < 40% down to $\sqrt{s_{NN}}$=7.7 GeV $v_3^2\{2\} \neq 0$. In disagreement with non-QGP models. $v_3^2\{2\}/n_{ch,PP}$ shows a minimum near $\sqrt{s_{NN}}$=20 GeV.
  - Charge-independent and beam-energy localized (19.6 and 27 GeV) structure observed in $R_2(\Delta y)$ extending as a ridge in $30^o < \Delta\phi < 150^o$ & $210^o < \Delta\phi < 330^o$
  - K^+/π ratio peaks at $\sqrt{s_{NN}}$ ~ 8 GeV, i.e. @ maximal net-baryon density.
  - Net-p shows non-monotonic energy dependence in the most central collisions starting at $\sqrt{s_{NN}}$ < 27 GeV.

- **Search for the critical endpoint continues:**
  - BES-II program is scheduled for 2019-20.
  - Fixed target program executed jointly with the CBM is scheduled for 2019. It will extend the measurements up to μ_B≈750 MeV.

STAR Collaboration

Thank You

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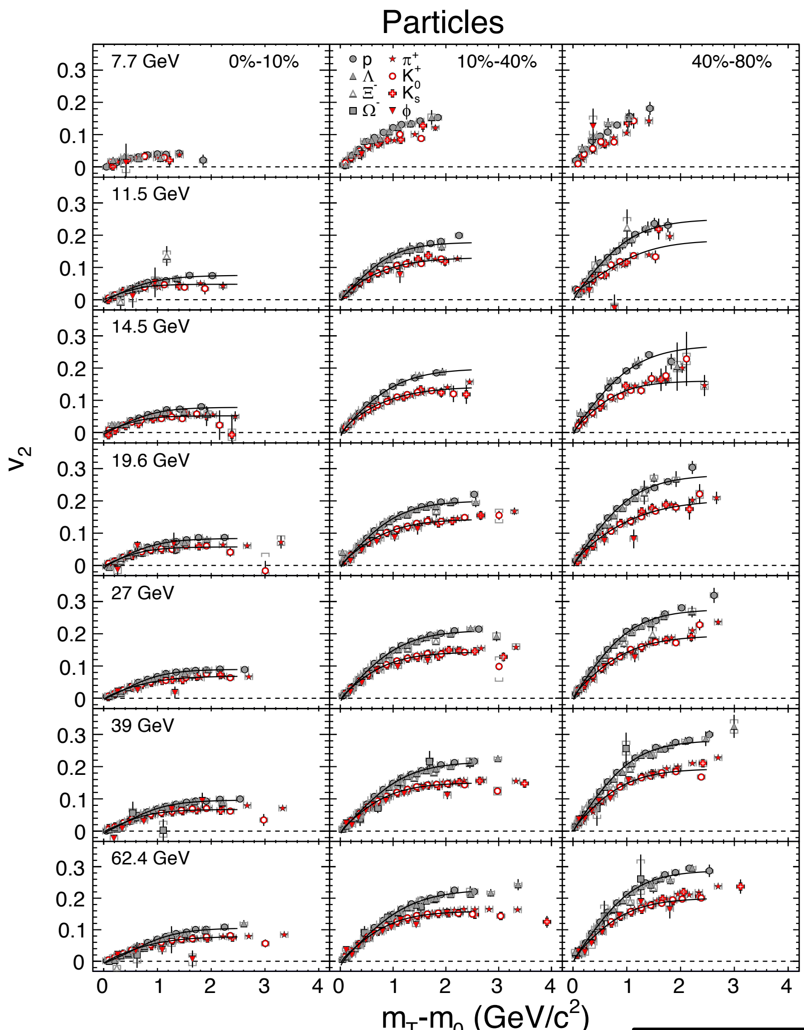
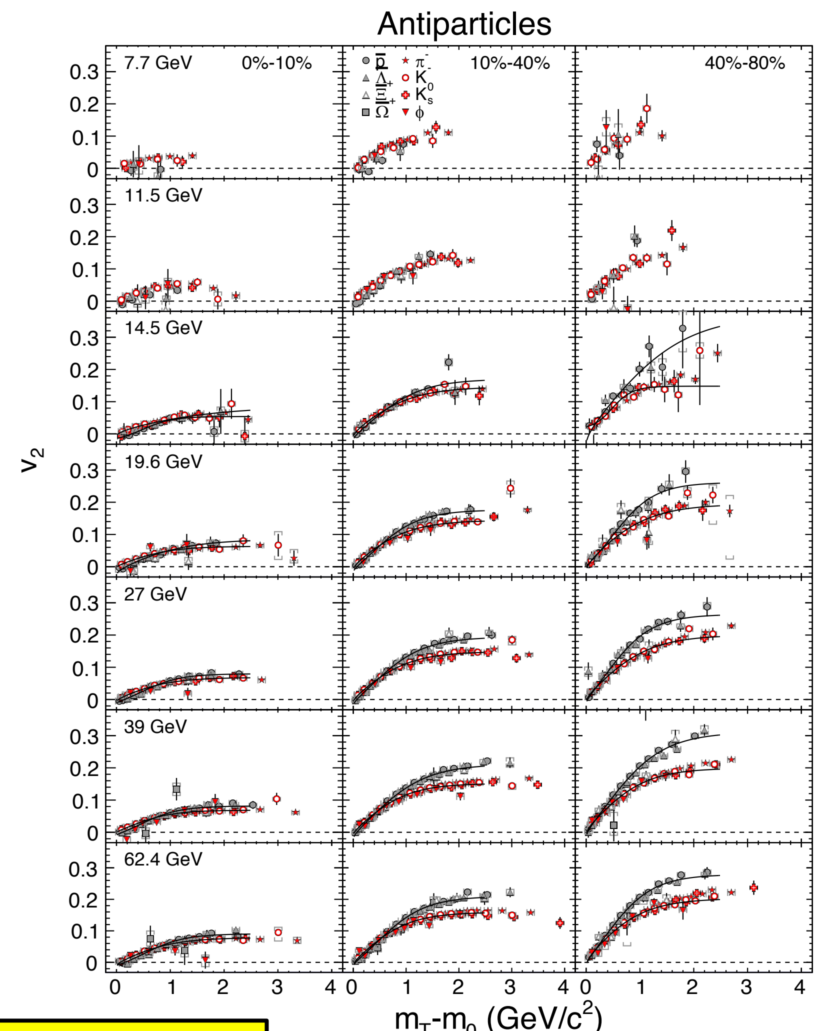
Backup slides

Elliptic flow of identified (anti)particles



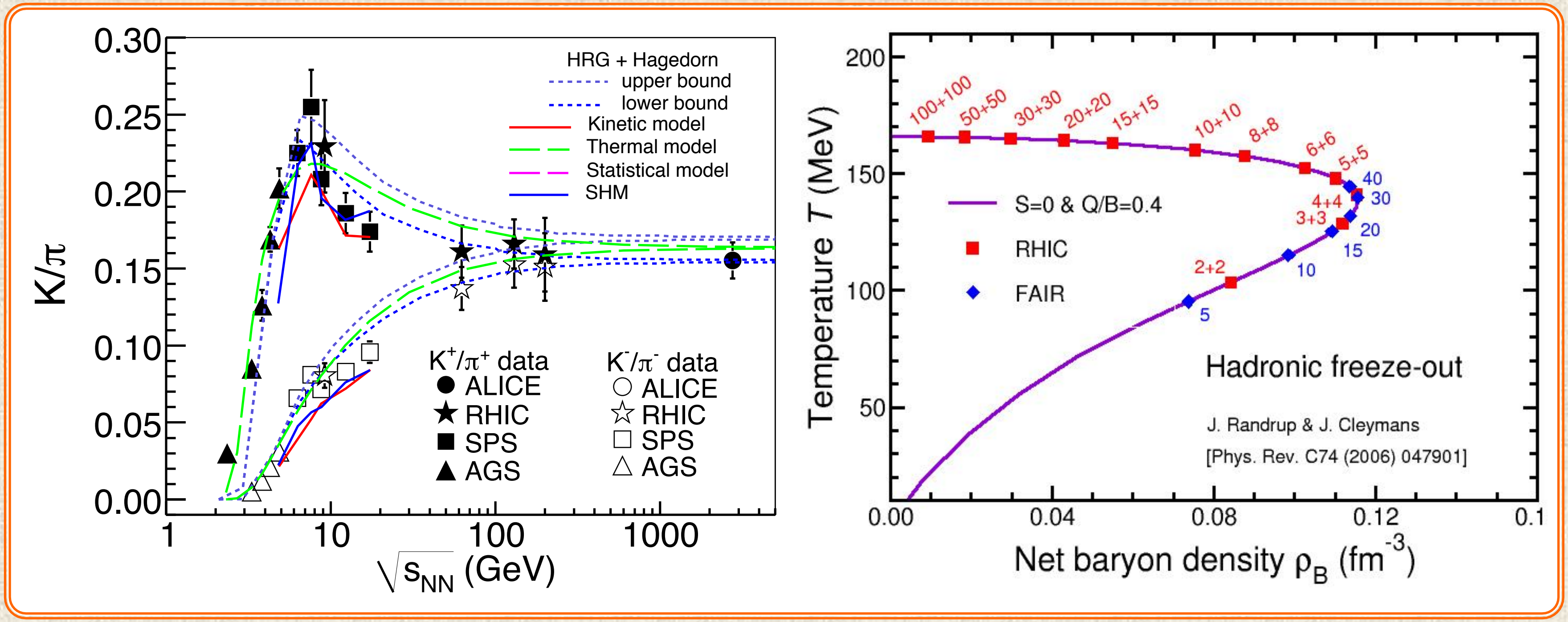
$\sqrt{s_{NN}}$



STAR: Phys.Rev. C93, 014907 (2016)

Starting from 14.5 GeV similar relative v_2 baryon-meson splitting is observed for all centralities (and agrees within 15% with the NCQ quark scaling – see line fits).
The larger v_2 for most particles relative to antiparticles shows a clear centrality dependence.

K/π Ratios and Baryon Density

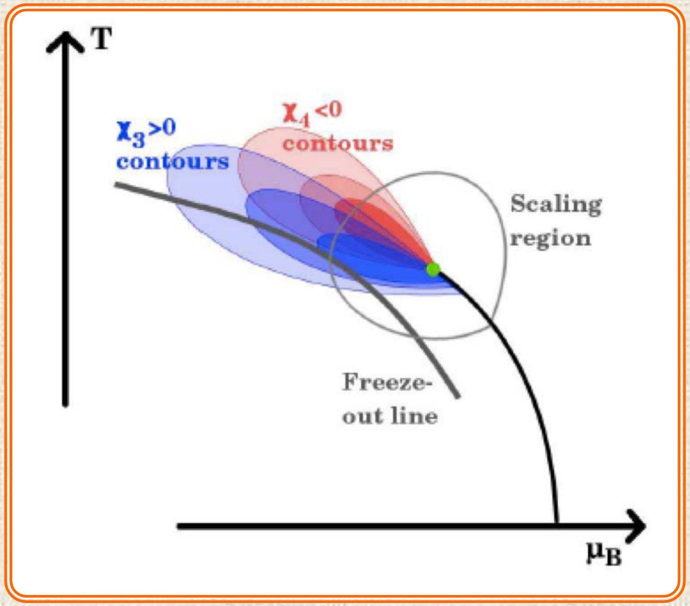


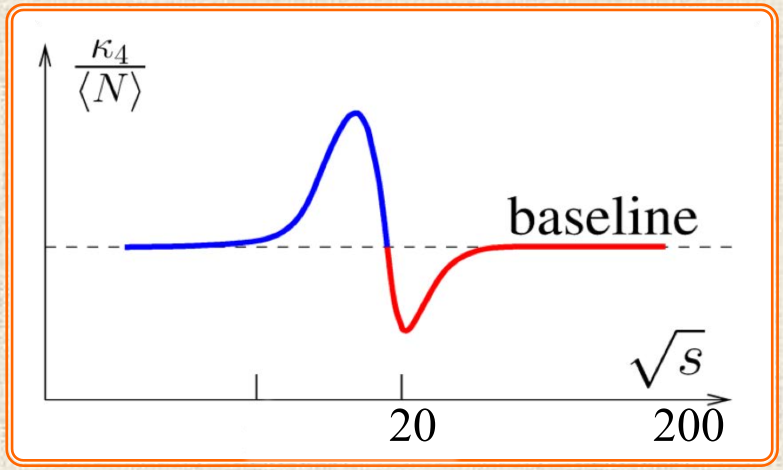
1) The K^+/π ratio peaks at $\sqrt{s_{NN}}$ ~ 8 GeV,
   K^-/π ratio merges with K^+/π at higher collision energy
2) Model: **Net baryon density peaks at $\sqrt{s_{NN}}$ ~ 8 GeV**
3) At **$\sqrt{s_{NN}}$ > 8 GeV, pair production becomes important**

Expectation from Model Calculations

$$\frac{p}{T^4} = \frac{1}{VT^3}\ln Z(T,\mu_u,\mu_d,\mu_s) = \sum_{ijk}\frac{1}{i!j!k!}\chi_{ijk}^{uds}\left(\frac{\mu_u}{T}\right)^i\left(\frac{\mu_d}{T}\right)^i\left(\frac{\mu_s}{T}\right)^j$$

$$\chi_2^X = \frac{1}{VT^3}\langle N_X^2\rangle, \qquad \chi_4^X = \frac{1}{VT^3}\left(\langle N_X^4\rangle - 3\langle N_X^2\rangle^2\right)$$





- Characteristic "Oscillating pattern" is expected for the QCD critical point but *the exact shape depends on the location of freeze-out with respect to the location of CEP*

- M. Stephanov, ***PRL107***, 052301(2011)
- V. Skokov, Quark Matter 2012
- J.W. Chen, J. Deng, H. Kohyyama, arXiv: 1603.05198, Phys. Rev. **D93** (2016) 034037

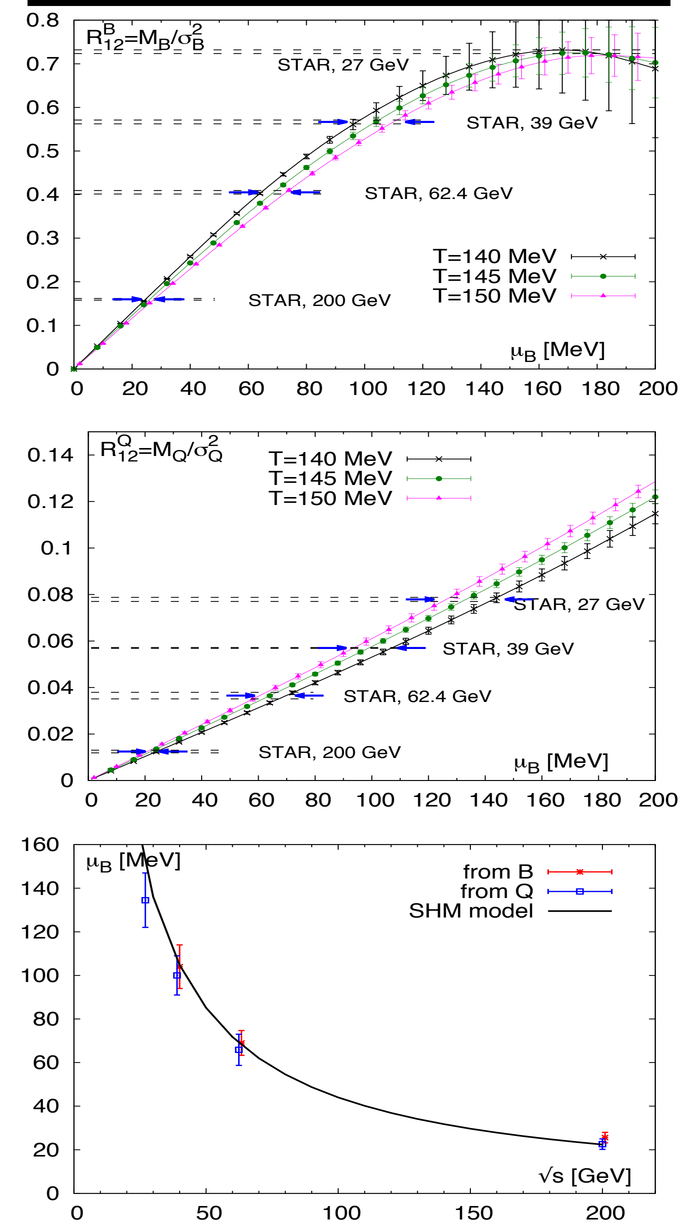
N.B. For $\mu_Q = \mu_S = 0$ the leading-order correction to the pressure at non-vanishing μ_B is proportional to the quadratic fluctuations of the net baryon number:

$$\frac{p(T,\mu_B)-p(T,0)}{T^4} = \frac{1}{2}\chi_2^B(T)\left(\frac{\mu_B}{T}\right)^2\left[1+\frac{1}{12}\frac{\chi_4^B(T)}{\chi_2^B(T)}\left(\frac{\mu_B}{T}\right)^2\right] + \mathcal{O}(\mu_B^6)$$

Comparison of net-baryon and net-charge moments at higher energies with LQCD

- Continuum extrapolated LQCD calculations with 2+1 dynamical flavors at physical mass for u,d and s quarks.
- Upper value of the freeze-out temperature T_f and baryon chemical potential μ_B were extracted.
- Consistency between T_f and μ_B from baryon number and electric charge fluctuations were found.
- The freeze-out chemical potentials agree with SHM

S. Borsanyi *et* al., PRL 113, 052301 (2014)



Simple Example of CEP: Liquid-Gas Phase Transition of Nuclear Matter

VDW equation with Fermi statistics

$$p(T,\mu) = p^{\mathrm{id}}(T,\mu^*) - a\,n^2(T,\mu)$$

$$n(T,\mu) = \frac{n^{\mathrm{id}}(T,\mu^*)}{1 + b\,n^{\mathrm{id}}(T,\mu^*)},$$

Parameters a and b are fixed to reproduce the properties of nuclear matter in its ground state i.e. at T=0
$p = 0$, $n = n_0 \sim = 0.16\ \mathrm{fm}^{-3}$, and $E_B = E/N - m \sim -16$ MeV.

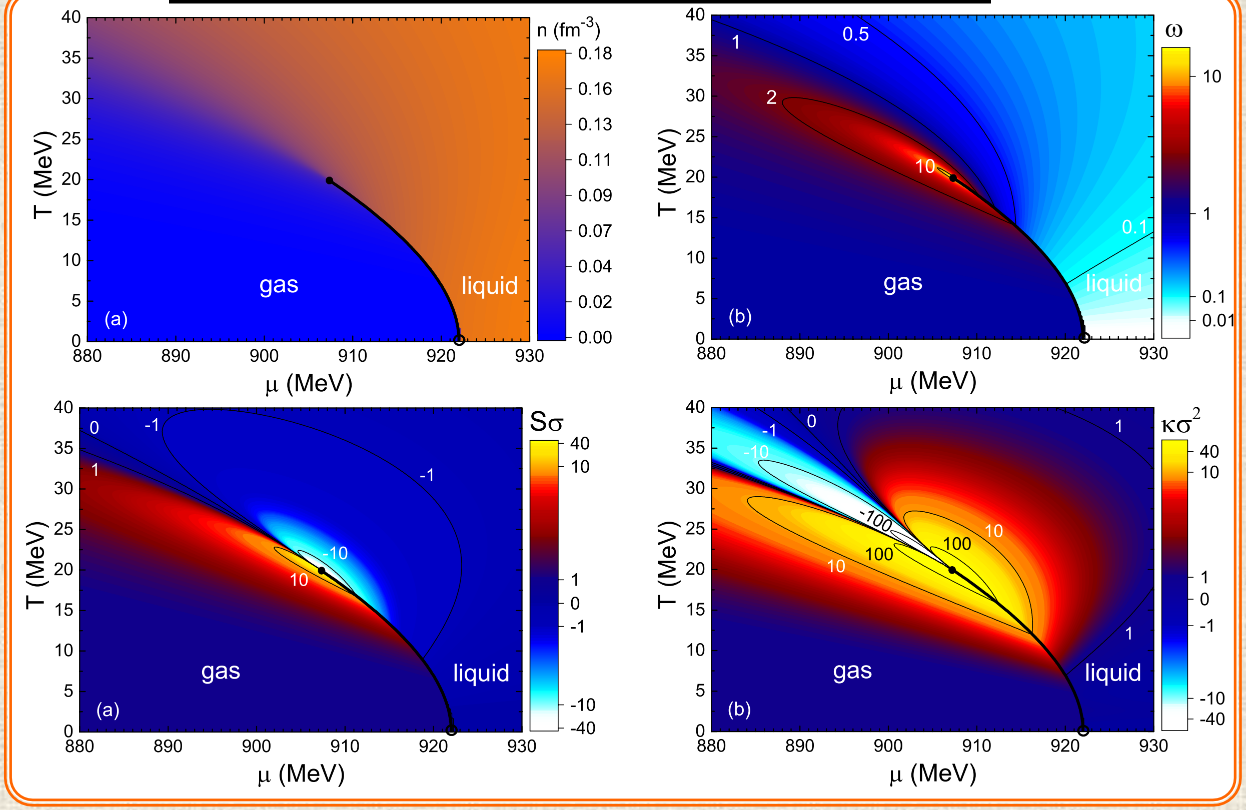
Extracted values of T_c and n_c differ marginally from the experimental ones.

$$\omega[N] = \frac{\langle(\Delta N)^2\rangle}{\langle N\rangle},$$

$$S\sigma = \frac{\langle(\Delta N)^3\rangle}{\langle(\Delta N)^2\rangle},$$

$$\kappa\sigma^2 = \frac{\langle(\Delta N)^4\rangle - 3\langle(\Delta N)^2\rangle^2}{\langle(\Delta N)^2\rangle}$$

V. Vovchenko *et al.*, Phys.Rev. C92 (2015) 5, 054901



The rich structures of the skewness and kurtosis observed in the wide T -μ area around the CEP of nuclear matter.